DIFFERENTIAL ADSORPTION OF K, CA AND MG BY TROPICAL SOILS AND THEIR UPTAKE BY KIKUYUGRASS

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By

Wang Ki Yu

Dissertation Committee

Yusuf N. Tamimi, Chairman
Samir A. El-Swaify
Yoshinori Kanehiro
Wallace G. Sanford
Charles M. Campbell

We certify that we have read this dissertation and that in our opinion it is satisfactory in scope and quality as a dissertation for the degree of Doctor of Philosophy in Agronomy and Soil Science.

Dissertation Committee

Yusuf N. Tamimi
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Chairman

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\-------------------------------

\-------------------------------

Charles M. Campbell
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ABSTRACT

The differential adsorption of K, Ca and Mg at pH 5.0 and 6.0 by Maile, Hawi and Wahiawa soils representing an Inceptisol, a Mollisol and an Oxisol, respectively, was established at 25 C. The cationic concentration of the equilibrating solutions containing cationic pairs of K:Ca, K:Mg and Mg:Ca were adjusted to 0.1 N. The cationic ratios were 1:1, 1:2, 1:4 and 1:8. Equilibrium was achieved over a 12-day period.

When equilibrating in 0.1 N solution chlorides of K, Ca and Mg, the three soils adsorbed more K, Ca and Mg, respectively, at pH 6.0 than at pH 5.0. At the same time, all the three soils adsorbed more Ca than Mg and then K at each pH level.

The Maile and Hawi series preferentially adsorbed divalent cations (Ca and Mg) over monovalent cation (K) at both pH 5.0 and 6.0. Between the two divalent cations, Ca was preferentially adsorbed over Mg by the two soils. In the case of the Wahiawa soil, monovalent cation (K) was selectively adsorbed over divalent cations (Ca and Mg) at both pH levels. Between Ca and Mg, Wahiawa soil preferentially adsorbed Ca over Mg.

The effects of various levels of K, Ca and Mg on dry matter yield, mineral composition and grass tetany ratio

of kikuyugrass were investigated by a greenhouse experiment in two soils at pH 5.0 and 6.0. The two soils were Maile and Wahiawa soils representing an Inceptisol and an Oxisol, respectively. The greenhouse experiment was a 3x3x3 (KxCaxMg) factorial design with three replicates.

The total dry matter production of kikuyugrass increased with increasing application of K and Mg in both soils at the two pH levels. Increasing application of Ca to Wahiawa soil significantly increased the dry matter production of kikuyugrass, however, in the case of the Maile soil, it was not affected significantly.

Tissue K, Ca and Mg concentrations and uptake of these three elements by kikuyugrass increased with increasing applied K, Ca and Mg, respectively, in both soils at the two pH levels. Tissue Ca concentration of kikuyugrass decreased significantly with increasing applied K and Mg; however, tissue Mg level was not influenced by the application of Ca in Maile and Wahiawa soils at both pH 5.0 and 6.0. At the same time, the application of K decreased tissue Mg concentration of kikuyugrass grown in both soils at the two pH levels. The application of Ca and Mg to both soils did not produce any significant effect on the tissue K concentration of kikuyugrass at the two pH levels.

The grass tetany ratio of kikuyugrass grown in the two soils increased with increasing applied soil K. Such an increasing trend was enhanced by the lowering of the applied soil Mg level. Applied Ca did not affect the grass tetany ratio of kikuyugrass in both soils at the two pH levels. Concentrations of P, S and Zn in tissue of kikuyugrass decreased with increasing K in both soils at the two pH levels. In the two soils, tissue S concentration of kikuyugrass increased with increasing soil Mg at both pH levels.

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INTRODUCTION

Ion selectivity by soil refers to a process in which certain cations or anions are preferentially adsorbed or retained on the adsorption sites of the soil colloids. Ions which are not retained or adsorbed are eventually lost through leaching. These adsorbed ions provide most of the nutrient requirements for plants. Ion selectivity by soil colloids depends on the nature of ions, soil physico-chemical and mineralogical properties, as well as soil environment. Hence, all these factors also influence the nutrient uptake by plants.

Grass tetany (Hypomagnesemia), a disease which affects the central nervous system of ruminant animals, is caused by a low Mg level in the blood serum of the affected animal which is either related to a low Mg level in the animal's diet or poor absorption of Mg in the animal's intestinal tract, or both. Cattle affected by grass tetany will show the loss of coordination of legs, which in advanced stages may lead to paralysis. Other symptoms of grass tetany in cattle including nervousness, hypersensitivity towards human beings, excess urination and defacation and convulsion which if not treated promptly will lead to the death of the animal.

The deficiency of Mg in the tetany-affected ruminant animals is closely related to a nutrient imbalance among soil, plant and animal system. Allaway (1962) suggested an imbalance might be result when:

a. the requirement for a certain nutrient by the animal is much greater than the plant's need for normal growth;

b. the plant accumulates certain nutrients to levels which are toxic to the animal or interfering with the ultilization of other nutrients;

c. the requirement of a given nutrient for normal growth by both plant and animal is similar, a deficiency of this nutrient in the soil may restrict the noraml growth of both plant and animal.

The value of 2.2 or above in the ratio of K/(Ca+Mg) on equivalence basis in forage consumed by ruminant animals is regarded by many scientists as an indicatior to predict the possible occurrence of grass tetany (Kemp and t'Hart, 1957; Butler, 1963). Such a ratio may depend on the balance of K, Ca and Mg in soil on which the plant grows.

The problem of grass tetany has been widely reported in temperate areas, especially in Europe where it is considered to be a problem in livestock production. However, relatively scant inforamtion on grass tetany in the Tropics is available. Recently, Carlson (1976) reported incidences of grass tetany on Huehue Ranch on the Island of Hawaii. Although most of the cases involved three to four herds at a time, this could not be compared to the massive death of cattle on the Continental U.S. In order to have a better understanding of this problem, it is necessary to investigate both soil and plant factors. Once these factors are understood, solution may be achieved thus preventing serious economical losses. Therefore the objectives of this research were:

1. To investigate the differential adsorption of K, Ca and Mg by three tropical soils at two pH levels.

2. To determine the uptake of K, Ca and Mg by kikuyugrass (Pennisetum clandestinum Hochst. ex Chiov.) as affected by soil type and soil K, Ca and Mg contents at two pH level.

LITERATURE REVIEW

Historical Aspects of Grass Tetany

Grass tetany has been widely reported in Europe, North America, New Zealand and Australia. Reid and Jung (1947) reported animal losses due to grass tetany reached a level of 0.5% for all dairy cows in the United Kingdom and 1-2% of dairy animals in the Netherlands. Hjerpe (1964) reported that during 1963-1964, death losses from herds in California attributed to grass tetany were as high as 20%. Grass tetany has also been reported in some parts of North America. Horvath (1959) noted the occurrence of grass tetany in beef cattle in West Virginia. Crookshank and Sim (1955) concluded that pregnant cows grazing on wheat pasture were the most susceptible to grass tetany. Underwood (1966) found that grass tetany generally affected mature ruminant animals or those in the late stages of pregnancy. They attributed this to the inability of older animals to mobilize Mg from their skeletons.

Indices for Predicting the Occurrence of Grass Tetany

The variation in mineral composition due to plant species has been well documented (Todd, 1966; Reid et al, 1970). Kemp and t'Hart (1957) suggested the value of

2.2, which is a ratio of K/(Ca+Mg) in the forage on equivalence basis, to be a critical level above which grass tetany was most likely to occur. Kemp (1960) concluded that when Mg level in grass reached a level of 0.2% or higher, grass tetany would be most unlikely to occur. Todd and Morrison (1964) and de Groot (1966) proposed a safe value of 0.25% for forage Mg for milk production and the health of the grazing dairy cows. Another approach by Butler (1963) demonstrated that the ratio of K/(Ca+Mg) on equivalence basis in the forage was more reliable than the Mg content alone for predicting the incidence of grass tetany. As such, any species of forage plants which contain the ratio K/(Ca+Mg) greater than 2.2 is regarded tetany prone. By using the ratio technique, Thill and George (1975) demonstrated in a field trial in central Iowa that temperate grass species such as reed canarygrass, orchardgrass, tall oatgrass and Canada wildrye were most likely to cause grass tetany in ruminant animals. Occurrence of grass tetany has been reported on orchardgrass in West Virginia (Horvath, 1959), crested wheatgrass in Nevada, Idaho and Utah (Miller, 1965), smooth brome grass in Iowa (George and Thill, 1979) and hardinggrass in Texas (Read, 1980). Tamimi et al (1976) found that under variable soil K, Ca and Mg conditions, the ratio of K/(Ca+Mg) on equivalence basis in pangolagrass was always below 2.2 while in certain treatments, kikuyugrass achieved a ratio as high as 3.0. They attributed this phenomenon to the ability of kikuyugrass to accumulate more K than pangolagrass.

Effects of Some Soil Characteristics on Nutrients Uptake by Plants

The incidence of grass tetany in ruminant animals is closely related to the cationic ratio in tissue of the forage, while the uptake of cations by plants is affected by soil cationic balances. The availability of certain nutrients to plants is closely related to their retention on the soil colloidal surfaces. In pasture where most nutrients are subjected to the continuous leaching process, those retained on the adsorptive sites will hence form the major pool of available nutrients for plant growth. The retention of nutrients on the soil colloidal surfaces is due to a number of forces namely electrostatic attraction, van der Waal force, and chemical bonding. These forces or energies have to be overcome before any nutrient in ionic form can be released from the soil surface and subsequently taken up by plants.

Cation exchange in soils

The retention of various cations on exchange surfaces can be represented by a cation exchange equation. An example of an exchange reaction involving cations can be illustrated by considering mineral soil colloidal surfaces high in adsorbed K, Ca and Mg, functioning at optimium moisture and temperature. The H ions generated from the decomposition of soil organic matter tend to replace the exchangeable cations on the soil colloids. The reaction can be illustrated by a schematic diagram in Fig. 1. Since the reaction is a reversible one, it's direction is governed by the Principle of Mass Action reaction. The released cations from such an exchange are either taken up by plants or lost through leaching to the lower soil profile.

Marshall (1948) suggested that the exchangeable ions of a given kind were not held with the same bonding energy on all clay minerals. Nutrients which are retained on the exchange sites of the soil colloids can be released through the exchange with the respective complementary ions. Jarusov (1937) concluded that the exchangeability of a cation was a function of its degree of saturation as well as the exchangeability of the accompanying cation. McLean and Marshall (1948) reported that the bonding energy between Ca and montmorillonite increased by three folds as the Ca-saturation changed from 70% to 90%. Jenny and Ayres (1939) formulated the Complementary Ion Principle in Exchange for finite exchange by assuming that each ion possessed a certain mean oscillation volume near a charged surface. Wiklander (1946) stressed the importance of the activity coefficient

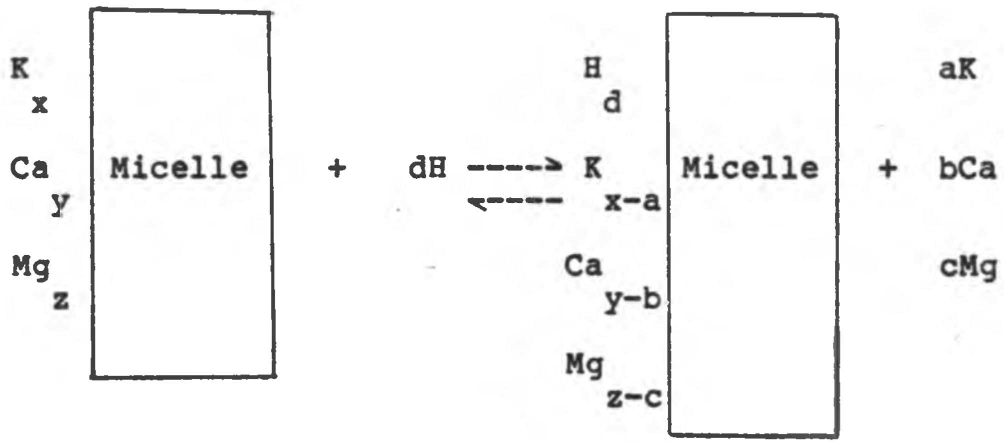

Fig. 1. A schematic diagram illustrating an exchange reaction on soil.

of each ion participating in the exchange process. Glueckauf and Kitt (1955) reported an inverse relationship between hydration diameter of divalent cations and the selectivity of these cations by soils.

Birrell (1961) successfully explained the order of adsorption namely La > Ba > Rb on Tirau ash subsoil by using the hydration radius data of Glueckauf. Gast (1969) concluded that the adsorption of monovalent cation from strong electrolyte solution by Wyoming bentonite was determined by their hydration radii. Tummavuori and Aho (1980) found that cation adsorption by peat was not affected by the ionic radius in the case of Li, Na, K, Rb and Cs; however, the ionic radii did affect the adsorption of alkaline earth metals such as Mg, Ca, Sr and Be.

Differential adsorption of cations by soils

Heald (1960) proposed that the existence of "loose" and "tight" sites on clay minerals was due to the difference of the bonding energy with various ions. van Bladel and Gheyi (1980) studied the Ca-Na and Ca-Mg exchange equilibrium on calcareous soils and reported that the Ca preference was associated with the organic phase of the soil. Khasawneh et al (1968) defined the selectivity coefficient K, between Ca and Sr in the following manner:

$$K = [Sr\text{-}soil]/[Ca\text{-}soil] \times (Ca)/(Sr)$$

where the parenthesis indicates activities of ions in solution while the bracket stands for the concentration of exchange ions. If the soil adsorbed Sr preferentially to Ca, K will be greater than unity. When $K<1$, Ca is adsorbed preferentially to Sr. Hunsaker and Pratt (1971) reported the preference for Ca in the Ca-Mg exchange equilibrium with an allophane and a Dystrandept. A similar observation on three Chilean Andepts was also reported by Galindo and Bingham (1977). Sposito et al (1983) advocated that the preference for Ca over Mg by a Wyoming bentonite was the result of the formation of the more thermodynamically stable CaCl complexes which also possessed a greater affinity for the clay than the MgCl complexes. Levy et al (1983) observed that the preference for Ca over Mg by bentonite was not affected by the presence of exchangeable Na. More recently, Fletcher et al (1984) showed that the preference for Ca over Mg by a Attamont clay loam (montmorillonitic) was not affected by pH in the range between 5 and 7 as well as soil sodium exchange percentage (ESP) up to 25%.

Ananthanarayana and Rao (1977) established the Mg retention trend among various Indian soils to be in the following order:

laterite > black soils > lateritic soil

They concluded that affinity and bonding energy of Mg were important factors in the Mg retention on the above soils.

The retention of metallic ions on oxidic surfaces has attracted the attention of many investigators. Huang and Stumm (1937) reported the relative affinity of alumina for alkaline earth metal ions followed the sequence of:

$$Mg > Ca > Sr > Ba$$

The mechanism of such an adsorption, unlike the non-specific electrostatic attraction between hydrated ions and charged surfaces of the clay minerals, involves the interaction between the metallic ion and the clay structural oxygen. Nalovic et al (1957) and Kinniburgh (1976) both observed the strong association between heavy metallic ions and oxides and they proposed that the importance of oxidic minerals in the retention of heavy metals in soils. McBride (1978) in his study of adsorption of Cu, Ca, Mg and Mn by amorphous alumina by using electron spin resonance (ESR) and specific ion electrode technique, reported that at pH 4.5, Cu was selectively retained on the alumina while Ca, Mg and Mn were not. He attributed this interaction to the bond formation between Cu and clay surface structural oxygen atom derived from the displacement of protons from hydroxyl groups.

Information concerning the preference for divalent over monovalent cations in the retention process on clay surfaces is well documented (Bolt, 1955; Bower, 1959).

Eaton and Sakoloff (1935) were the first to observed the electro-selectivity phenomenon increased with decreasing electrolyte concentration which was later referred to as "valency dilution" effect. McLean and Marshall (1948) reported that the bonding energy between Ca and montmorillonite to be 1348 cal/mole as compared to 710 cal/mole for K. Gessa (1970) concluded that the pH-dependent exchange sites of allophane had a strong preference for divalent over monovalent cations. Wiedenfeld and Hossner (1978) derived theoretical exchange equations by using solid phase activity coefficient and thermodynamic equilibrium constant for three binary systems obtained from experimental data for a tertiary system containing three heterovalent cations. They successfully predicted that the divalent Ca and Mg would have relatively higher affinities than the monovalent Na for exchange sites of a montmorillonitic Argiaquoll. Similarities in affinities between Ca and Mg were also observed.

Hutcheon (1966) suggested that charge magnitude was not the sole reason that a divalent cation was more strongly bound to the soil than a monovalent cation; the distance between the ions and the charged surfaces and the hydration energy would modify the charge effect. Sinanuwong and El-Swaify (1974) demonstrated preferential adsorption of divalent cations (Ca and Mg) over monovalent cation (Na) on Lualualei and Honouliuli soils when they investigated the exchange behavior of some irrigated Hawaiian Vertisols dominated by montmorillonite. They also reported that the surface horizons of the above two soils retained more Na than the underlying horizons. van Bladel and Gheyi (1980) observed that Ca was more selectively adsorbed over Na or Mg in a calcareous soil dominated by montmorillonite and they attributed this to the overall entropy change during the exchange process. Ananthanarayana and Rao (1980) also confirmed the preferential adsorption of divalent cations (Ca and Mg) over monovalent cation (Na) on some soils of Karnataka in India. McLean and Marshall (1948) confirmed that different clays possessed different bonding energies for a given cation; for example, K-montmorillonite=710 cal/mole and K-beidellite=1544 cal/mole, Ca-montmorillonite=1396 cal/mole and Ca-beidellite=2670 cal/mole.

The relative retention between Al and Ca on soil surfaces has been investigated by Nye et al (1961). They reported that Al was always preferably adsorbed over Ca on smectite, kaolinite and two North Carolina Ultisols. However, the competitive adsorption between Al and K was less defined than that of Al and Ca. Singh and Talibudeen (1971) observed in some Malaysian latosols that K was adsorbed more strongly than Al at low K loading. Pleysier et al (1979) studied the exchange behavior of several magnesium Vertisols and established the order of preferential adsorption among several cations such as K, Ca, Mg and Al as follows:

$$K > Al > Ca > Mg$$

van Bladel and Menzel (1969), Jensen (1973) and Udo (1978) attributed the preferential adsorption of K by kaolinite to the specific interaction of the cation with the edge site of the minerals and such an interaction would generate a high negative free energy value during the exchange of such cation. More recently, Jardin and Sparks (1984) observed that K was preferred over Ca by the Ap horizon of an Evesboro soil from Delaware when the mole fraction (N) of K in the solution was low; however, at high value of (N), Ca was selectively adsorbed.

Effects of pH on cation retention by soils

The importance of pH in the retention of nutrients is particularly shown in soils or clay minerals exhibiting pH-dependency of charge characteristic. Ayres (1944) reported that the retention of potassium and ammonium salts on some Hawaiian soils could be enhanced by reducing the acidity. Tamimi et al (1974) studied the cation exchange capacity of a Hawaiian Andept (Maile series) in a field study and concluded that more K and Mg were retained in the furrow slice against leaching at higher soil pH level due to a substantial increase in cation exchange capacity of the soil. In a pot study conducted by Haveraaen (1978) on a poorly humified soil, the leaching loss of K applied as carbonate was found to be less than when applied as chloride. More recently, Pleysier and Juo (1981) found that limed soil column retained more Ca in the surface layer than in column which received equal amount of Ca applied as nitrate. The retention of heavy metallic cations as affected by soil pH has also been investigated by several researchers. Kinniburgh et al (1976) demonstrated that at pH 5.0, more Cu than Zn was retained on the amorphous alumina. Hatton and Pickering (1980) concluded that the amount of Cu, Pb, Zn or Cd retained by clay-humic mixture varied markedly with the pH, nature of the clay and the chemical properties of the organic components. James and Healy (1972) reported that the adsorption of Co and Ca on silica was pH dependent. Tummavuori and Aho (1980) revealed that pH of the solution was the most crucial factor in the retention of heavy metals by peat. Hence it is quite obvious that the retention properties of soils depend on the nature of the ions, soil mineralogy, soil organic matter and soil pH.

Leaching losses of soil nutrients

Water soluble nutrients such as N, K, Ca and Mg which are not retained by soil colloids will be leached down to the lower soil profile beyond the reach of plant roots. The loss of nutrients by this process has been well documented. Fukushi et al (1977) studied the effect of applied cattle manure on leaching losses of various nutrients from a humus-rich Andosol and reported that under manure, leaching was greatest for N, followed by Cl and Na, and to a smaller extent by K, Mg and Ca. Tummavuori (1980) confirmed that ammonium-N was not retained by the peat thus allowing it to be lost through leaching. Tamimi (1980) reported that leaching losses of N and K in Hawaiian Histosols were excessive while that of P was minimal. Getmenets and Avramenko (1976) observed in the Ukrainian Steppe Zone that the movement of nitrate down the profile was greatest in the autumn and winter while in the dry summer months, leaching was limited and nitrate usually moved upwards. They also related the downward and upward movements of nitrate in the field to the amount of rainfall and winter freezing conditions, respectively. Marion and Leaf (1977) demonstrated in a 3-year lysimeter experiment on a glacial outwash plain in the Adirondack Mountain of New York that the leaching of KCl was significant during the initial year of application and the K concentration in the leachates remained high during the following two years. They also observed that application of K-fertilizer increased the downward movement of Ca, Mg and Na. Stark and Zuuring (1981) succeeded in using some physical and chemical properties of soil such as texture and cation exchange capacity to predict the nutrient retention capacity of soils in an undisturbed column. At the same time, they also reported that ion storage for soil high in salts and organic matter was difficult to predict. Neilsen and Stevenson (1983) studied the leaching loss of K, Ca and Mg under intense irrigation and N-fertilization in an apple orchard and reported that Ca and Mg leached more rapidly than K in all lysimeters; however, they did not specify the soil type in the orchard. Messick et al (1984) reported that the leaching of Ca and Mg decreased with increasing soil clay content; thus indicating the importance of clay minerals in the cation retention process.

Effects of soil fertilization

Since grass tetany is associated with low Mg level in the forage which is probably caused by a low level of available soil Mg, the incidence of such a disorder can be reduced through Mg fertilization. Metson et al (1966) and Grunes (1967) succeeded in increasing the forage Mg content by applying Mg-fertilizer on acidic and coarse texture soils. However, on the heavier soils, the effect of the application of Mg-fertilizer on the uptake of Mg by plants was much less obvious (Kemp, 1971; Price and Moschler, 1970; Grunes, 1973; Hannaway et al, 1980; Wilkinson and Stuedemenn, 1979). Finn and Shannon (1976) demonstrated that increasing applied Mg progressively increased the Mg content of sudangrass in a greenhouse trial. They also concluded that the forage Mg content of sudangrass could be raised to 0.2% or above by reducing the available soil Ca:Mg ratio from 30:1 to 10:1 through the addition of Mg-fertilizer. Gross (1973) and Hogg and Karlovsky (1968) also reported that a higher Mg content in forage could be achieved by the application of a Mg-containing fertilizer called Kierserite.

The effects of N-fertilizer on the uptake of K, Ca and Mg by plants has been studied by many researchers. Azih (1978) found that leaf K concentration in two varieties of maize increased with increasing N-fertilizer, while in the case of Ca and Mg, the relationship were not clear. A study conducted by Stewart et al (1981) on the chemical composition of winter wheat forage found that the concentration of K increased with increasing N. while those of Ca and Mg were not affected significantly. Penny et al (1980) reported that Mg content in timothy and meadow fescue increased with increasing N application. Maeta et al (1980) studied the effect of four rates of N-fertilizer on the mineral content of cocksfoot and they reported that Ca and Mg contents of the herbage were lowest at the lowest N rate (1200 kg/ha/year). Probasco and Bjugstad (1980) reported that the application of 54 kg/ha each of nitrogen, phosphorus pentoxide and potassium failed to increase the Ca content of tall fescue in the Osark region of south Missouri. Gashaw and Mugwira (1981) concluded from a greenhouse study that fertilization with either ammonium or nitrate-N increased the uptake of Ca, Mg, Mn and nitrate-N in triticale, wheat and rye. Collin and Balasko (1981) showed that N-fertilizer increased K and Mg concentrations but not Ca in the tissue of the "Ky 31" tall fescue. Eck et al (1981) investigated the effects of N-fertilization and irrigation regimes on the quality of tall fescue and smooth bromegrass. They found that potassium and nitrate-N concentrations of both forages increased with increasing N-fertilization. They also observed that N-fertilization increased the Mg concentration in tall fescue but not in smooth bromegrass. Mayland et al (1975) demonstrated that N-fertilizer increased the concentrations of forage Mg and Ca more than the increase in K in crested wheatgrass where the forage K/(Ca+Mg) ratio on equilvalence basis remained below the 2.2 critical limit. Alston (1966) and Kershaw and Banton (1965) demonstrated in oats and ryegrass, respectively, that increasing N-fertilization increased the forage N but decreased the blood Mg level of the grazing animals; this might trigger grass tetany, even though forage Mg in both grasses increased with increasing N-fertilization rate. Kemp et al (1961) attributed the above situation to the release of high level of ammonium cations in the rumen of animals consuming grass fertilized with high rate of N-fertilizer and the subsequent precipitation of the blood Mg as magnesium ammonium phosphate. Kemp et al (1966) further suggested that the relatively high fatty acid content in the plant as a result of increase in N-fertilization might lead to the formation of insoluble Mg soaps in the gastrointestinal tract of the ruminants thus triggering grass tetany through the lowering of blood Mg. Since there is a strong evidence that the application of high levels of N and K-fertilizers may increase the risk of grass tetany, a compromise between high forage yield which can be brought about by utilizing high rate of N-fertilizer and the risk of grass tetany has to be made. Wolton (1963) advocated that excess N-fertilizer should not be used in forage production and K-fertilization should be delayed until the danger period was over.

Effects of Some Plant Characteristics on Nutrients Uptake by Plants

Several factors determine the mineral content of plant tissue including plant species, the variety of the given species as well as the growth stages of plants. Tamimi et al (1976) obtained data from a greenhouse study showing pangolagrass extracted more Na and less K from soil than did kikuyugrass. Mattson et al (1949) reported that pea root (high CEC) absorbed more Ca and less K than did barley (low CEC). As a result of such demonstration, they concluded that the relative amount of divalent to monovalent cations absorbed by root depended on the CEC of the root. Recent investigation conducted by some researchers such as Read (1980) on tall fescue, Mayland et al (1976) and Karlen et al (1978) on wheat, and Robertson et al (1965) and Azih (1978) on maize, indicated that there were significant differences in the mineral uptake among varieties of a given species of plant grown under identical conditions.

The difference in the accumulation of nutrients at various growth stages of a given species of plant has also been observed by many investigators. Tamimi et al (1968) observed variation in K, Ca and Mg contents of kikuyugrass harvested at different heights. Westfall et al (1973) found the concentrations of N, P and K were highest in the younger, fully mature leaves of rice and decreased with leaf age. Again, Tamimi et al (1978) reported that the concentrations of N, P, K, Ca and Mg in corn grown in Kohala region on the Island of Hawaii decreased significantly with plant age. Czuba (1969) and Miller (1939) reported that most K uptake occurred before flowering in winter wheat. Waldren and Flowerday (1979) reported that the uptake of P and K by winter wheat were most rapid from culm elongation to anthesis stages. van Riper and Smith (1959) conducted research on the mineral composition of alfalfa and concluded that both K and Mg concentrations decreased with stages of growth; however, the lack of a systematic trend between stages of growth and Ca content was also observed. Karlen et al (1978) reported that the concentrations of K, Ca and Mg in leaf, crown and root of wheat were higher at the 15-day period than the 37-day period after emergence. Amos et al (1975) found that Mg concentration in early spring orchardgrass was higher in the vegetative stage than in the heading stage. Follet et al (1975) did not find any significant variation in the Mg level among various growth stages in smooth bromegrass. Schwartz and Kafkafi (1978) studied the relationship between mineral composition and growth stages in field grown maize and wheat and reported that that K, Ca and Mg concentrations in both plants decreased with growth. The same trend was also observed by Stewart et al (1981) on winter wheat grown in Texas and Okalahoma. Bosovic (1980) attributed the decrease in the average mineral content of cocksfoot, timothy, meadow fescue, red clover and birdsfoot trefoil with increasing maturity to the increase in the stem:leaf ratio and that the mineral content of the stem was lower than that of the leaf. As a result of the variation in the mineral content with growth stages, the cationic ratio of K/(Ca+Mg) may change accordingly. In order to use the cationic ratio of a forage plant to predict grass tetany, growth stages of the plant has to be taken into account.

Effect of Some Environmental Factors on Nutrients Uptake by Plants

Effects of soil moisture, temperature and oxygen levels

It has long been confirmed that the mineral uptake by plants is affected by the micro-environmental factors in which they live. Soil, which is a component of the micro-environment, exerts its impact on the mineral uptake by plants through some of its physical parameters including moisture, temperature and oxygen levels. Reitemeir (1945) demonstrated that upon dilution, Ca and Mg readily replaced ammonium, potassium and sodium ions from soil colloids, thus affecting the cation balance in soil which in turn influenced the nutrient uptake by plants. McNaught et al (1969) observed variation in the Mg content of grass induced by variable solar radiation, soil temperature and soil moisture levels. Grunes et al (1970) related grass tetany to high soil water content and cool temperature. Elkins and Hoveland (1978) showed that Mg content of annual ryegrass increased with increasing soil oxygen level and they also suggested that the effect of oxygen on K, Ca and Mg uptake by plants was plant species dependent. Elkins et al (1978) demonstrated in both field and greenhouse experiments that low oxygen level resulted from poor drainage might decrease Mg concentration in tall fescue forage. Karlen et al (1978) observed that soil moisture content, plant cultivar and translocation mechanism of nutrients affected the cationic concentration of wheat grown in the growth chamber. Marshall (1977) and Reitemeir (1945) applied the Principle of Thermodynamics (Donna Theory) to explain the fact that activities of divalent cations such as Ca and Mg in soil solution decreased with increasing soil moisture level (decreasing soil oxygen); such a trend would raise the tissue K/(Ca+Mg) ratio which in turn may trigger grass tetany.

Effects of some atmospheric conditions

Along with the micro-environment, the atmospheric conditions also exerts its influence on the mineral composition of plants. Jakrlova (1979) performed chemical analysis on the above-ground biomass collected during a 2-year period from a natural grassland dominated by *Nardus stricta*, *Festuca rubra*, *Festuca sulcata* and *Sanfuisorba officinalis* and concluded that the variation in mineral contents between the two years was due to the difference in climatic conditions. Thill and George (1975) observed that the cationic ratio of K/(Ca+Mg) in plants fluctuated with seasonal changes expressed in the form of temperature. They also observed the increase in this ratio when the mean daily temperature rose above 14 C. George and Thill (1979) reported that in smooth bromegrass, an increase over 2.2 in the cationic ratio of

K/(Ca+Mg) and a decrease in the forage Mg content below 0.2% became serious during rainy periods when followed by a temperature rise above 14 C. Kemp and t'Hart (1957) showed a relatively higher incidence of grass tetany during spring and fall when rainfall was high. Horvath and Todd (1968) reported the occurrence of grass tetany during spring season. Carlon (1976) observed year-round incidence of grass tetany among cows in Hawaii, where the temperature variation was not as great as in temperate regions. He also observed the incidence of grass tetany was strongly associated with pasture located in areas of 100-125 cm annual rainfall and at elevation of 4500 feet and above. Read (1980) showed that the cationic ratio of K/(Ca+Mg) in hardinggrass and tall fescue was fluctuating when grown at temperature range between 11.3 C and 22.4 C with the highest ratio at approximately 18 C. They also reported that the K/(Ca+Mg) ratio in hardinggrass was much higher than that in tall fescue. More recently, West and Reynold (1984) reported that K concentration in tall fescue increased during spring growth and the change in the ratio of K/(Ca+Mg) followed the K trend. Hence all these works indicate that grass tetany is strongly influenced by climatic conditions in which the forage is grown.

MATERIALS AND METHODS

Soils

Three Hawaiian soil orders were represented in this study. They were selected to provide variable mineralogical and ion exchange characteristics. They were:

1.) Inceptisol (Maile Series), which was derived from volcanic ash.

2.) Oxisol (Wahiawa Series), which was developed from basalt.

3.) Mollisol (Hawi Series), which was also orginated from basalt.

The Wahiawa Series was collected at two locations and designated as Wahiawa (A) and Wahiawa(B), respectively. Wahiawa (A) was used in the laboratory study involving the differential adsorption of K, Ca and Mg while the Wahiawa (B), which possessed a low base saturation thus allowing for adjusting its fertility to the desired level, was used in the greenhouse experiment concerning the uptake of these three elements by kikuyugrass (Pennisetum clandestinum Hochst. ex Chiov.) at pH 5.0 and pH 6.0. The classification, mineralogical composition and chemical properties of each soil series are listed in Tables 1, 2 and 3, respectively.

Table 1. Taxonomic designation of soils investigated (*)

Series	Order	Subgroup	Family	Sampled Depth (cm)	Parental Material
Maile	Inceptisol	Hydric dystrandept	Thixotropic isomesic	15-60	Volcanic ash
Hawi	Mollisol	Typic haplustoll	Fine, kaolinitic, isohyperthermic	5-30	Basalt
Wahiawa	Oxisol	Tropetic eutrustix	Clayey, kaolinitic, isohyperthermic	5-30	Basalt

(*) Taxonomy information was obtained from Soil Survey, Laboratory Data and Descriptions for Some Soils of Hawaii, Soil Survey Investigations Report No. 29. Soil Conservation Service, United States Department of Agriculture.

Table 2. Mineralogical composition of the soils investigated (*).

Soil	He	Py	Ka	Gi	Mg	Go	An	Il	Qu	Ma	Ru	Ha	Mi	Am	Psed
	(%)														
Maile	--	--	--	--	--	--	--	--	+	+	--	+	--	25	--
Hawi	11	--	--	4	15	13	--	10	10	--	4	11	--	15	4
Wahiawa (A)	12	6	15	--	10	6	8	12	8	10	4	--	5	5	--
Wahiawa (B)	15	--	13	12	--	11	11	11	10	10	--	4	--	5	--

Legend

He = Hematite
Ka = Kaolinite
Gi = Gibbsite
Ha = Halloysite
An = Anatase

Py = Pyrochorite
Ma = Magnetite
Ru = Rutile
Go = Goethite
Am = Amorphous Material

Qu = Quartz
Il = Ilmenite
Mg = Maghemite
Mi = Mica
Psed = Pseudo-brookite

+ Detected but not quantified.
(*) Courtesy of Dr. Rollin C. Jones, Department of Agronomy and Soil Science, University of Hawaii-Manoa.

Table 3. Chemical analysis of soils investigated.

Soil	pH a/	Extractable Cations b/ K	Ca	Mg	O.M. c/	P d/	CEC e/
		----me/100g----			%	ppm	me/100g
Maile	5.05	0.01	0.20	0.03	15.5	4.5	64.9
Hawi	5.54	4.06	20.22	18.09	19.9	216.2	54.9
Wahiawa (A)	5.02	0.73	0.60	0.26	5.2	95.6	21.9
Wahiawa (B)	3.85	0.05	0.05	0.03	5.0	7.0	18.3

a/ pH of the saturated soil paste.
b/ By 1 N ammonium acetate (adjusted to pH 7.0) method.
c/ Organic matter content was obtained by the Walkley-Black method.
d/ Extractable P was determined by the modified Troug method of Ayres and Hagihara (1952).
e/ Cation Exchange Capacity was established by 1 N ammonium acetate (adjusted to pH 7.0) saturation.

Methods

Soil sampling

The site of the sampled Maile Series was in the forest reserve area at Hamakua Farm on the Island of Hawaii. Two samples of the Wahiawa Series were taken. Wahiawa (A) was obtained from a site at the Paomoho Experimental Station where an erosion project was previously conducted while Wahiawa (B) was sampled from a pinapple field at Wahiawa, Oahu. The Hawi Series was collected at the Upolu area on the Island of Hawaii.

Soils for the laboratory study were sieved through a 0.8 mm (20 mesh) sieve while those used for the greenhouse experiments, a 6.4 mm (1/4 inch) sieve was employed. The sieved soils were mixed and stored in double plastic bags to minimize dehydration.

Soil preparation

Each soil was subdivided into two sub-samples which in turn were adjusted to pH 5.0 and 6.0, respectively. In the case of the Hawi series, where the original pH was 5.5, acidification process was conducted to bring the soil pH to 5.0. During the acidification process, the soil was shaken once with 0.02 N hydrochloric acid in a ratio of 1:2 (soil:acid by weight) for one hour, the suspension was then centrifuged and the supernatant discarded. The leached soil was subsequently washed with distilled water until it was free of chloride. The soil was then air dried and its pH determined. If the resulting pH was less than 5.0, the acidified soil was reconstituted with a certain amount of non-acidified sample until the desired pH was achieved. The acidification process was not needed for both Wahiawa (A) and Maile Series since their natural pH's were in the proximity of 5.0. To adjust the soils to pH 6.0, a soil buffer curve, constructed by applying various quantities of calcium carbonate to a certain amount of soil, was used (Fig. 2). The amount of calcium carbonate required to raise the soil pH to 6.0 in each soil was determined from its corresponding buffer curve. The chemical composition and the exchange characteristics of the treated soils are presented in Tables 4 and 5, respectively.

Soil characterization

1. pH

The pH of the saturated soil paste in water was determined by a Beckman Expandomatic pH meter equipped with reference and glass electrodes.

2. Exchangeable cations

The cations (K, Ca and Mg) on the selected soils were extracted with 1 N ammonium acetate solution adjusted to pH 7.0 with a soil:solution ratio of 1:20 and shaken for one hour (Jackson,1964). After filtering, the filtrate was analysed for these cations using an Atomic Absorption Spectrophotometer (Perkin Elmer, Model 603).

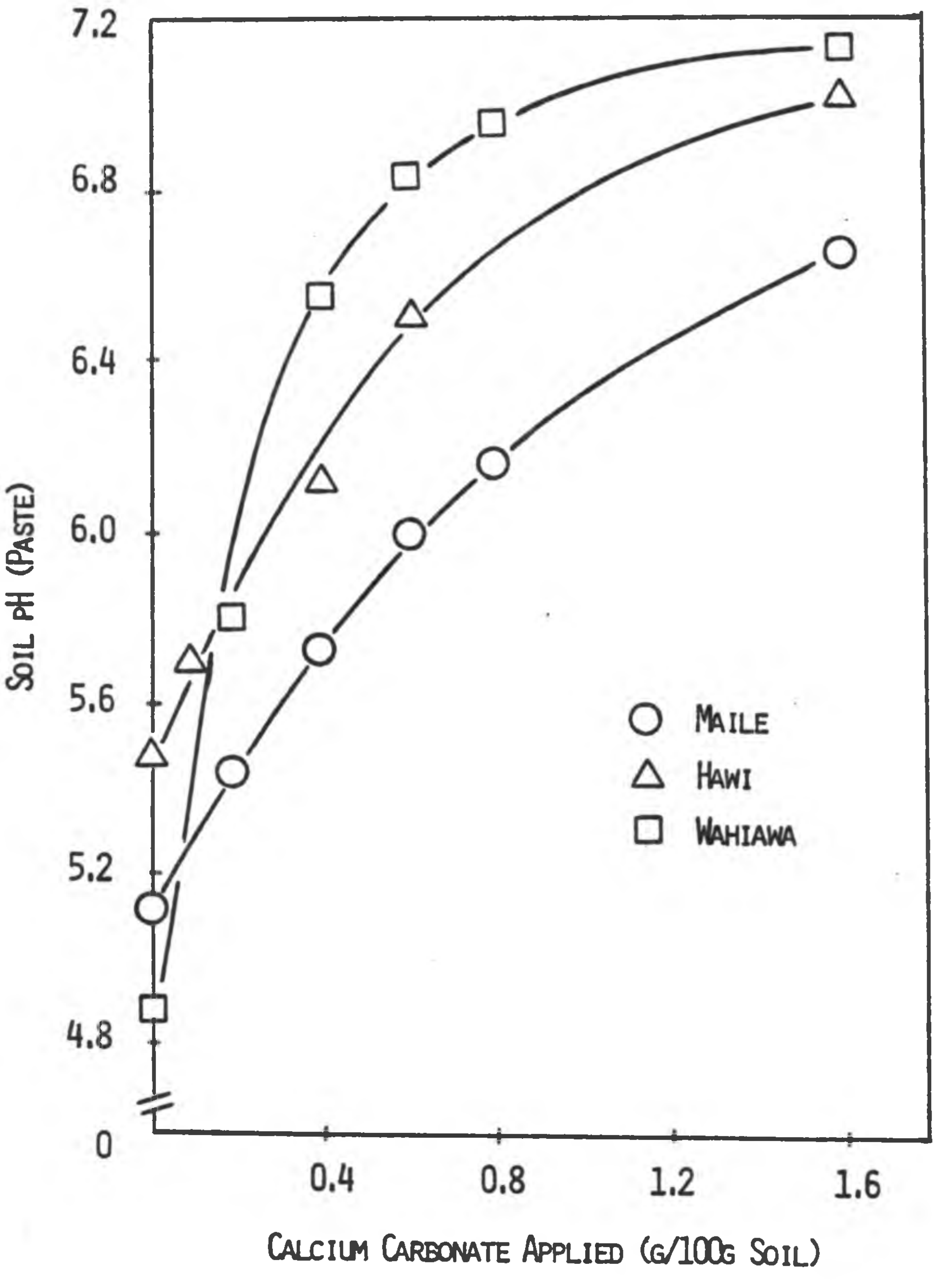

Fig. 2. Buffer curve for the selected soils.

Table 4. Chemical analysis of the prepared soils.

	Extractable Cations[c/]					
	K		Ca		Mg	
	5.0[a/]	6.0[b/]	5.0	6.0	5.0	6.0
Soil	me/100g					
Maile	0.01	0.01	0.20	10.02	0.03	0.03
Hawi	3.74	4.06	16.53	20.22	16.45	18.09
Wahiawa (A)	0.73	0.73	0.60	10.06	0.26	0.26
Wahiawa (B)	0.05	0.05	0.50	10.04	0.03	0.03

a/ Soil adjusted to pH 5.0.
b/ Soil adjusted to pH 6.0.
c/ Extractable cations were determined by 1 N ammonium acetate (adjusted to pH 7.0) method.

Table 5. Cation exchange capacity of the prepared soils

Soil	Cation Exchange Capacity pH 5.0 Ammonium Acetate a/	Chloride b/	pH 6.0 Ammonium Acetate	Chloride
	me/100g			
Maile	45.2	10.8	51.3	16.5
Hawi	48.1	41.3	51.3	44.0
Wahiawa (A)	15.7	10.1	16.3	12.2
Wahiawa (B)	14.6	10.0	15.2	13.4

a/ CEC determined by 1 N ammonium acetate solution adjusted to soil pH.
b/ CEC determined by 1 N ammonium chloride solution.

3. Extractable phosphorus

Soil phosphorus was extracted by 0.02 N sulfuric acid solution as developed by Ayres and Hagihara (1952).

4. Organic matter

Soil organic matter was determined by modifying the wet oxidation procedures outlined by Walkley and Black (1934). About 0.1g soil (oven dried basis) was weighed out on an analytical balance and was wet-oxidized with 10 ml of 1 N $K_2Cr_2O_7$ solution along with 20 ml conc. sulfuric acid. After the oxidation, 15 ml of phosphoric acid was added to the system and the unreacted $K_2Cr_2O_7$ was then titrated with 0.5 N N $FeSO_4$ solution in which barium diphenylamine sulfonate was used as indicator. The organic matter content was then calculated by the following equation:

$$\%O.M. = (A - B) \times 0.69 / \text{wt of soil}$$

where A and B are quantities of $K_2Cr_2O_7$ and $FeSO_4$ in milliequivalent, respectively.

5. Cation exchange capacity (CEC)

Two methods were used to determine the cation exchange capacity (CEC) of the treated soils. Sub-sample of the treated soils were shaken with 1 N ammonium acetate solution adjusted to the respective soil pH levels while the other sub-sample was saturated with 1 N ammonium chloride solution in which the pH was not adjusted. Both methods were allowed mild shaking for an hour. This was subsequently followed by the displacement of the adsorbed ammonium ions with 1 N potassium chloride solution and distillation of ammonia (Tamimi et al, 1975). Result of of the two methods employed (Table 5) showed that all three soils attained higher CEC at pH 6.0 than at 5.0, which was probably due to the existence of pH dependent charges on the soil surfaces. Cation exchange capacity (CEC) determined by the ammonium acetate saturation method consistently exhibited higher values than those obtained by the ammonium chloride method for the three selected soils series at both pH levels. This phenomenon may be caused by the generation of new adsorption sites resulting from the selective adsorption of acetate ions on the soil colloidal surfaces.

6. X-ray diffraction analysis

The mineralogical analysis of the three soils was conducted by a Hitachi X-ray diffractometer with the Cu K radiation and graphite monochrometer. Results of the mineralogical analysis are shown in Table 2.

Experimental Variables and Procedures

Differential adsorption of K, Ca and Mg on three tropical soils at two pH levels

Three tropical soils, an Inceptisol (Maile), a Mollisol (Hawi) and an Oxisol (Wahiawa A) from Hawaii were investigated for competitive adsorption of K, Ca and Mg at two pH levels. Soils were prepared as described earlier. The cationic ratios in the equilibrating solutions were 1:0, 1:1, 1:2, 1:4 and 1:8 for K:Ca, K:Mg and Mg:Ca on equilivalence basis. The equilibrating solutions whose concentrations were calibrated to 0.1 N using the chloride salts of these cations were prepared according to Table 37 in the Appendix. After the solutions had been prepared, they were adjusted to pH 5.0 and pH 6.0 by dilute hydrochloric acid.

5.0g of soil (oven dried basis) was weighed out and transferred to a centrifuge bottle to which 100 ml of the equilibrating solution was also added. The equilibration was carried out at 25 C with occassional shaking (15 min. mild shaking for every 12 hours). The length of equilibration was 12 days. The suspension was centrifuged and the cationic concentrations in the supernatant were analysed every 48 hours by the Atomic Absorption Spectrophotometer. The amount of cations disappeared from the supernatant was assumed to be adsorbed by soil. After the supernatant was decanted, another fresh portion of the equilibrating solution with the same cationic ratio was delivered to the centrifuged tube and the equilibrating process was repeated until an equilibrium was achieved. An equilibrium was indicated by a similar cationic concentration in both equilibrating and supernatant solution. The cationic concentrations of the supernatant liquid at the end of each equilibrating period were calculated. The selective adsorption of the cations by the soils was determined by a separation factor (C) defined in the following manner.

$$C = [A\text{-soil}]/[B\text{-soil}] \times (B)/(A)$$

where C is the separation factor; A and B are competitive cations; [A-soil]/[B-soil] is the ratio of cations adsorbed by the soil while (B)/(A) is the ratio of the two cations in the equilibrating solution. The concentration of cations in soil and liquid phases are expressed in me/100g and me/l, respectively. If the soil adsorbs cation A preferentially to cation B, then C will be greater than unity; if cation B is preferred over cation A, C will be less than unity. C will become unity when there is no preferential adsorption by the soil between cation A and cation B.

An exchange isotherm, established by plotting the equivalent fraction of the cation adsorbed, symbolized as Q/Qt, against the equivalent fraction in the equilibrating solution, C/Ct, was also employed to identify the preferential adsorption of a cation over the other by a particular soil. Hence, Q represents the amount of one of the two competing cations adsorbed in me/100g, Qt the sum of the two competing cations adsorbed in me/100g, C the concentration of one of the two competing cations in the equilibrating solution in me/l, and Ct the total concentration of the equilibrating solution expressed in me/l. The position of the exchange isotherm relative to the non-preference line determines the preferential adsorption of one cation over the other by a certain soil. If the isotherm lies above the non-preference line, the cation with which the construction of the isotherm is based, is preferenitally adsorbed over the other by the soil; if the isotherm lies below the non-preference line, such cation is not preferentially adsorbed when compared to the other competing cation in the equilibrating solution.

The uptake of K, Ca and Mg by kikuyugrass (*Pennisetum clandestinum* Hochst. ex Chiov.) as affected by soil type, and soil K, Ca and Mg levels at two pH levels

This study was conducted in the greenhouse on an Inceptisol (Maile) and an Oxisol (Wahiawa B). The experiment was a 3x3x3 (KxCaxMg) factorial design at two pH levels with three replicates for each treatment. After passing the soil through a 6.4 mm (1/4 inch) sieve, each soil was adjusted to pH 5.0 and 6.0 as outlined in the previous Method section (Soil preparation). The Ca levels associated with pH 5.0 and 6.0 for both Maile and Wahiawa (B) soils were 5.0 and 10.0 me/100g soil, respectively. In order to have similar ratios among K, Ca and Mg in both pH levels, rates of these three cations were calibrated in the following manner:

The Ca status of both soils was adjusted to 5.0, 7.0 and 9.0 me/100g soil for pH 5.0 and 10.0, 14.0 and 18.0 me/100g soil for pH 6.0. The three rates of Mg at pH 5.0 were 0.4, 1.2 and 3.6 me/100g soil, while at pH 6.0, the rates were 0.8, 2.4 and 7.2 me/100g soil. Potassium concentration were 0.1, 0.3 and 0.9 me/100g soil for pH 5.0 and 0.2, 0.6 and 1.8 me/100g soil for soils with pH 6.0. Calcium dihydrogen phosphate, calcium chloride and calcium nitrate were used as Ca-carriers. Magnesium was provided from magnesium chloride while potassium sulfate was the source of K.

Soils also received a blanket application of 200 ppm N from either ammonium nitrate and/or ammonium dihydrogen phosphate. Total amount of P was 1000 ppm derived from phosphoric acid, ammonium phosphate and/or calcium dihydrogen phosphate. Micronutrients were applied as follows: 15 ppm Cu from copper sulfate, 10 ppm B from boric acid and 30 ppm Zn from zinc sulfate. The treated soils were divided into three replicates each with 500g (oven dried basis) and placed into polyethylene bags. Each replicate was then contained in a 2-liter plastic pot. Due to the higher bulk density in the Wahiawa (B) soil than that of the Maile Series, each treatment with the Wahiawa (B) soil contained 2000g (oven dried basis) soil when compared to the 500g soil for Maile soil.

In order to have an identical genetic make up, all kikuyugrass cuttings were obtained by propagating in advance enough planting materials from a single clone. Prior to transplanting in the treated soils, cuttings were rooted in a vermiculite medium leached daily with a complete nutrient solution for ten days. Six kikuyugrass cuttings were allocated for each pot.

Four harvests each represented an average growth period of about six weeks were completed. The clipping height in each harvest was one inch above the soil surface. At the end of each harvest, K fertilizer was again applied to replenish what had been estimated to be taken up by the harvested portion of the plant. Such estimation was based on the data of a similar study by Tamimi et al (1976). Magnesium was applied in a similar fashion as K except that such an application was done at the end of the second harvest and onwards. Since the data obtained by Tamimi et al (1976) revealed that Ca removal by kikuyugrass was insignificant when compared to that in the soil, other than the amount applied at the beginning of the study, Ca was not reapplied subsequently. The various amount of K, Ca and Mg applied to Maile and Wahiawa (B) soils at pH 5.0 and 6.0 during the course of this study are summarized in Tables 6 and 7, respectively. In this report, the mean applications of K and Mg fertilizers per harvest were used in the data interpretation;

Table 6. Potassium, calcium and magnesium application to the Maile soil at pH 5.0 and pH 6.0 during the course of the study.

	Application (me/100g)									
	pH 5.0					pH 6.0				
Level	OA*	1st	2nd	3rd	Total	OA*	1st	2nd	3rd	Total
					--- K ---					
Low	.11	.11	.11	.11	.42	.21	.21	.21	.21	.84
Medium	.32	.32	.32	.32	1.26	.63	.63	.63	.63	2.52
High	.95	.95	.95	.95	3.78	1.89	1.89	1.89	1.89	6.72
					--- Ca ---					
Low	5.0	--	--	--	5.0	10.0	--	--	--	10.0
Medium	7.0	--	--	--	7.0	14.0	--	--	--	14.0
High	9.0	--	--	--	9.0	18.0	--	--	--	18.0
					--- Mg ---					
Low	.42	--	.42	.06	.90	.84	--	.47	.07	1.38
Medium	1.26	--	.68	.08	2.02	2.52	--	.71	.11	3.33
High	3.78	--	.81	.12	4.70	7.56	--	.86	.13	8.54

* Original application, prior to planting.

Table 7. Potassium, calcium and magnesium application to the Wahiawa (B) soil at pH 5.0 and pH 6.0 during the course of the study.

	Application (me/100g)									
	pH 5.0					pH 6.0				
Level	OA*	1st	2nd	3rd	Total	OA*	1st	2nd	3rd	Total
					--- K ---					
Low	.11	--	.11	.09	.31	.21	--	.15	.14	.50
Medium	.32	--	.27	.21	.80	.63	--	.36	.29	1.28
High	.95	--	.51	.35	1.81	1.89	--	.58	.49	2.96
					--- Ca ---					
Low	5.0	--	--	--	5.0	10.0	--	--	--	10.0
Medium	7.0	--	--	--	7.0	14.0	--	--	--	14.0
High	9.0	--	--	--	9.0	18.0	--	--	--	18.0
					--- Mg ---					
Low	.42	--	.08	.06	.56	.84	--	.10	.09	1.03
Medium	1.26	--	.14	.10	1.50	2.52	--	.16	.14	2.82
High	3.78	--	.18	.12	4.08	7.56	--	.21	.17	7.94

* Original application, prior to planting.

in the case of Ca, the initial application rates were employed. In addition to the 200 ppm N applied initially, 100 ppm of N as ammonium nitrate was also applied to each pot after each harvest.

The harvested portion of the grass was dried in a draft oven at 60 C for 48 hours. It was then ground by a stainless steel ball mill and subsquently tissue analysis was conducted by X-ray Fluorescence Quantometer. The tissue mineral concentrations used in this study were the weighted mean of the four harvests. After the fourth harvest, both Maile and Wahiawa soils were analysed for pH, P, K, Ca and Mg (Table 41 and Table 42 in the Appendix, respectively).

Analysis of variance was conducted on each harvest as well as on the weighted mean basis for parameters such as dry matter yield, concentrations and uptake of K, Ca, Mg, P, S, Cu and Zn by the top of the grass, and the grass tetany ratio, K/(Ca+Mg) on equilvalence basis, for each soil at both pH levels. Duncan Multiple Range Test was employed to determine the difference between means.

RESULTS AND DISCUSSION

Differential Adsorption of K, Ca and Mg by Three Tropical Soils at Two pH Levels

Adsorption of K from 0.1 N potassium chloride

The adsorption of K from 0.1 N potassium chloride solution by the Maile, Hawi and Wahiawa (A) soils are shown in Figs. 3, 4 and 5, respectively. The adsorption of K by the three soils increased with increasing equilibrating time. The adsorption process was completed in 12 days or less. Significantly more K was adsorbed at pH 6.0 than at 5.0 which might be due to the existence of pH dependent charges on these soils. The extent of such a difference in adsorption between these two pH levels was in the following order:

Hawi > Maile > Wahiawa (A)

The above trend is consistent with that of the soil organic matter content. Both soil organic matter and hydrated oxides of Al and Fe are associated with pH dependent charges; therefore, liming soils, such as Hawi and Maile dominated by these two components, respectively, would definitely increase the amount of adsorption sites. Although the organic matter content of Wahiawa (A) soil was the lowest among the three soils in this study, it did contain certain amount of materials such as hematite,

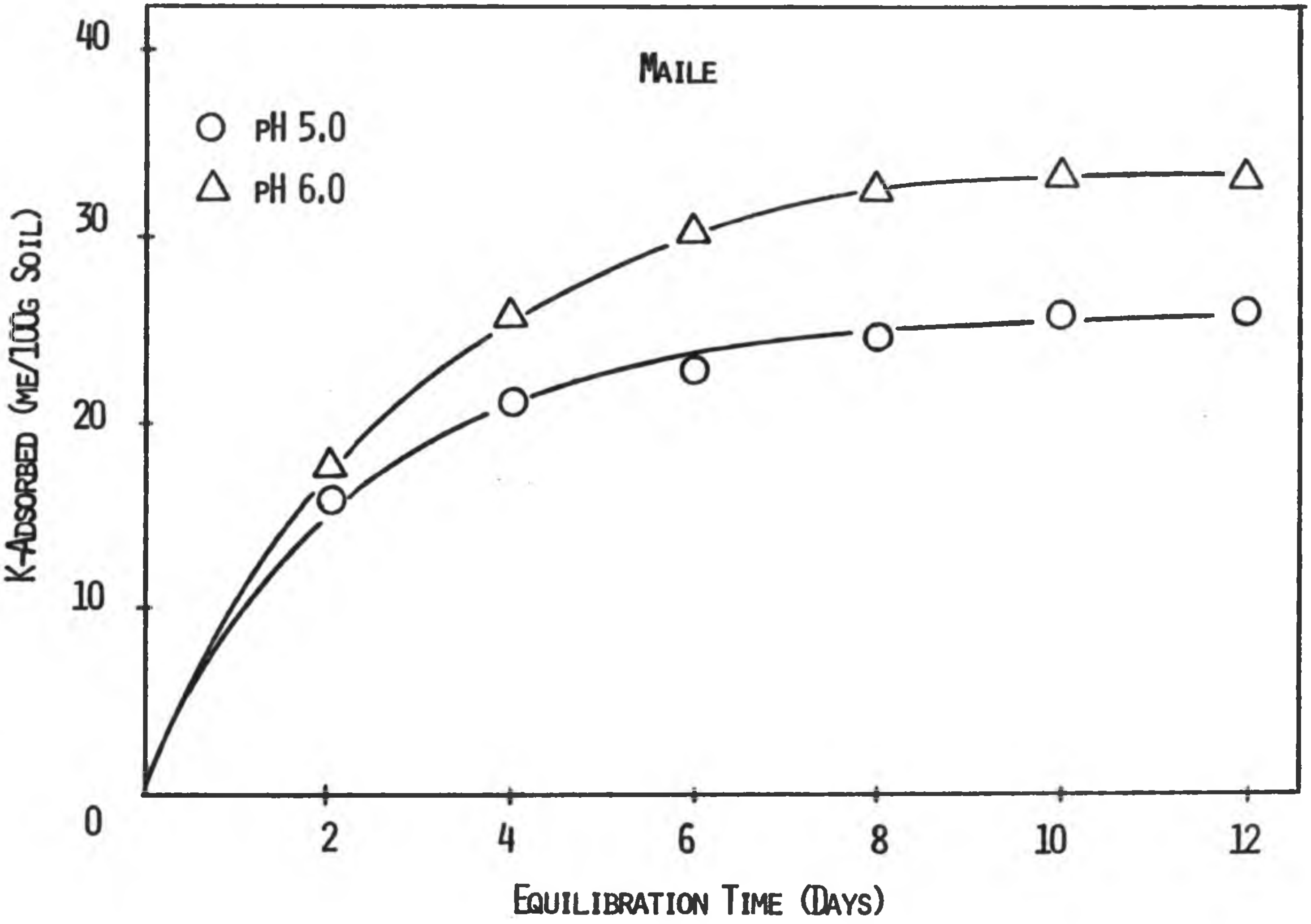

Fig. 3. Adsorption of K from 0.1 N potassium chloride solution.

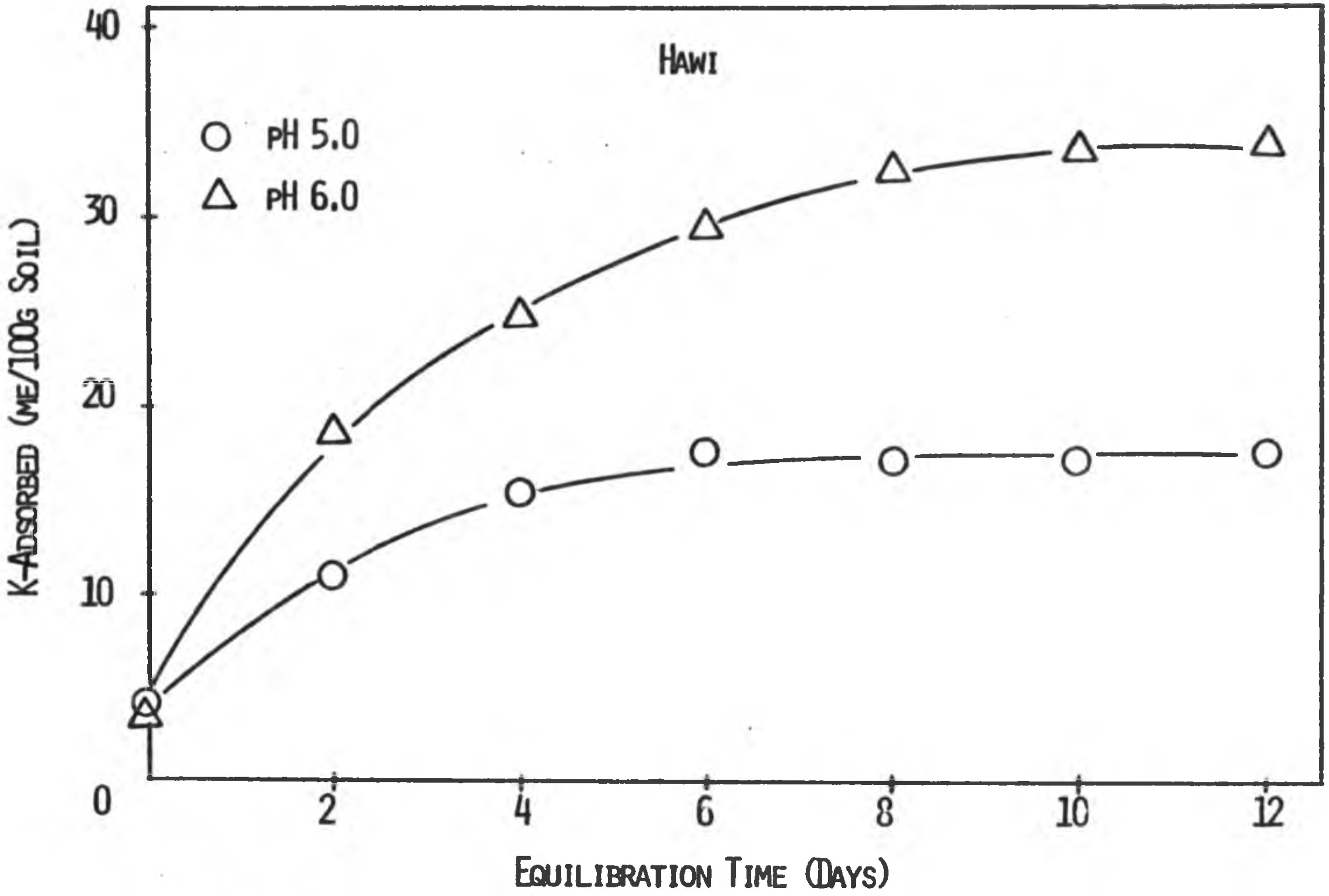

Fig. 4. Adsorption of K from 0.1 N potassium chloride solution.

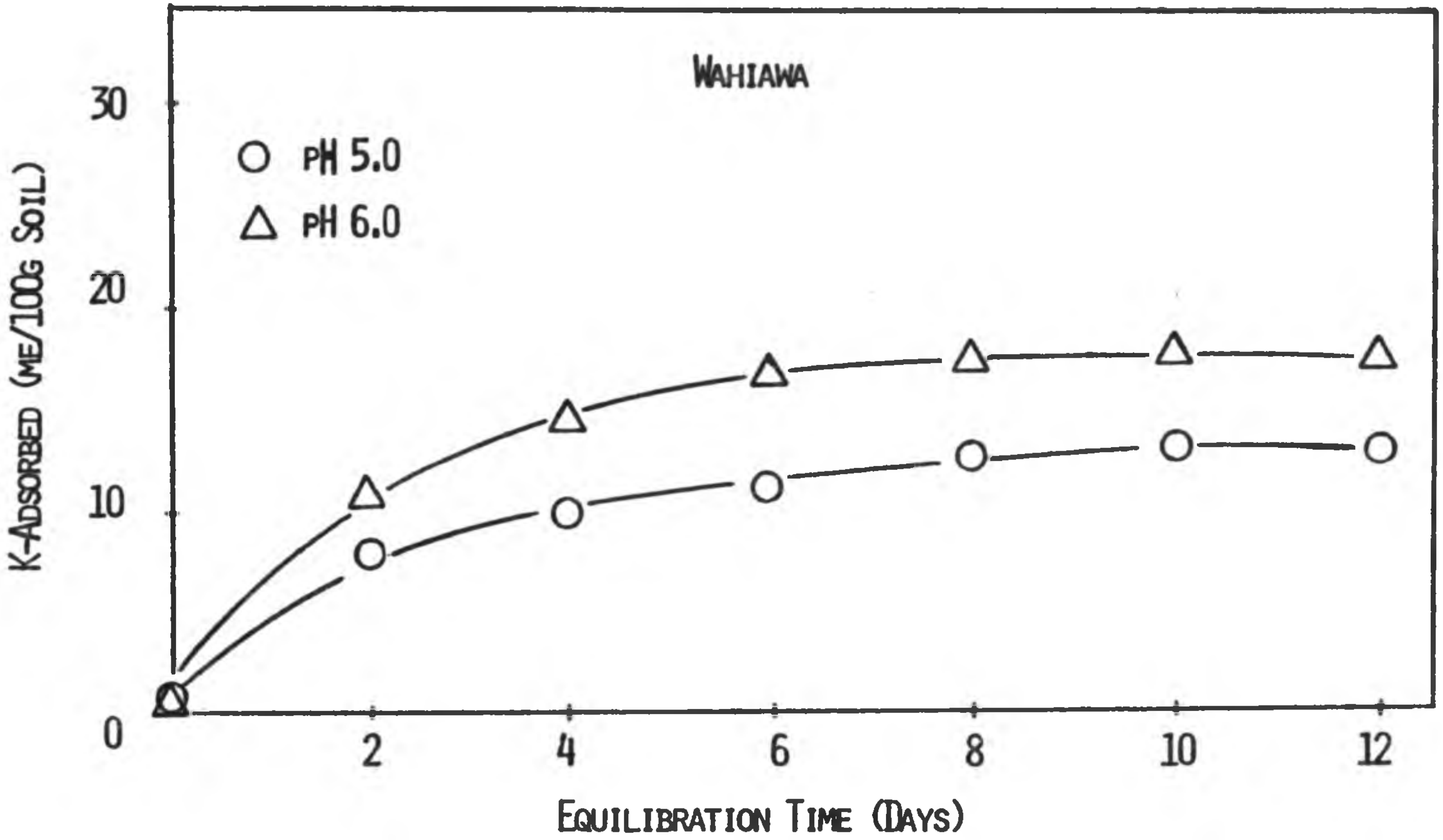

Fig. 5. Adsorption of K from 0.1 N potassium chloride solution.

kaolinite and amorphous substances (Table 2) which were responsible for pH dependent charges, thus also resulting in an increase of adsorption sites on liming. In Maile and Hawi soils where CEC at both pH 5.0 and 6.0 are high (Table 5), however, the adsorbed K at both pH levels just amounted to a fraction of the CEC value. Such a phenomenon can be attributed to the inability of K from the equilibrating solution to replace the major exchangeable cations which in this case are Ca and Mg in Hawi and Al and Fe in Maile amd Wahiawa (A) soils.

Adsorption of Ca from 0.1 N calcium chloride

The adsorption of Ca from 0.1 N calcium chloride solution by the Maile, Hawi and Wahiawa (A) soils are presented in Figs. 6, 7 and 8, respectively. In all three soils, the adsorption of Ca was completed in ten days or less. In the case of the Wahiawa (A) soil where the CEC is lower than those of the other two soils, 6-8 days were sufficient to bring about an equilibrium. Significantly more Ca was adsorbed at pH 6.0 than at 5.0. Unlike the adsorption of K, the amount of adsorbed Ca at both pH's represents a much greater fraction of the determined CEC for these soils; this together with the greater efficiency of the Ca adsorption than that of K among the three soils (less time needed to achieve equilibrium) indicate either Ca is a more powerful replacing cation than K or the existence of specific adsorption sites for Ca, or both.

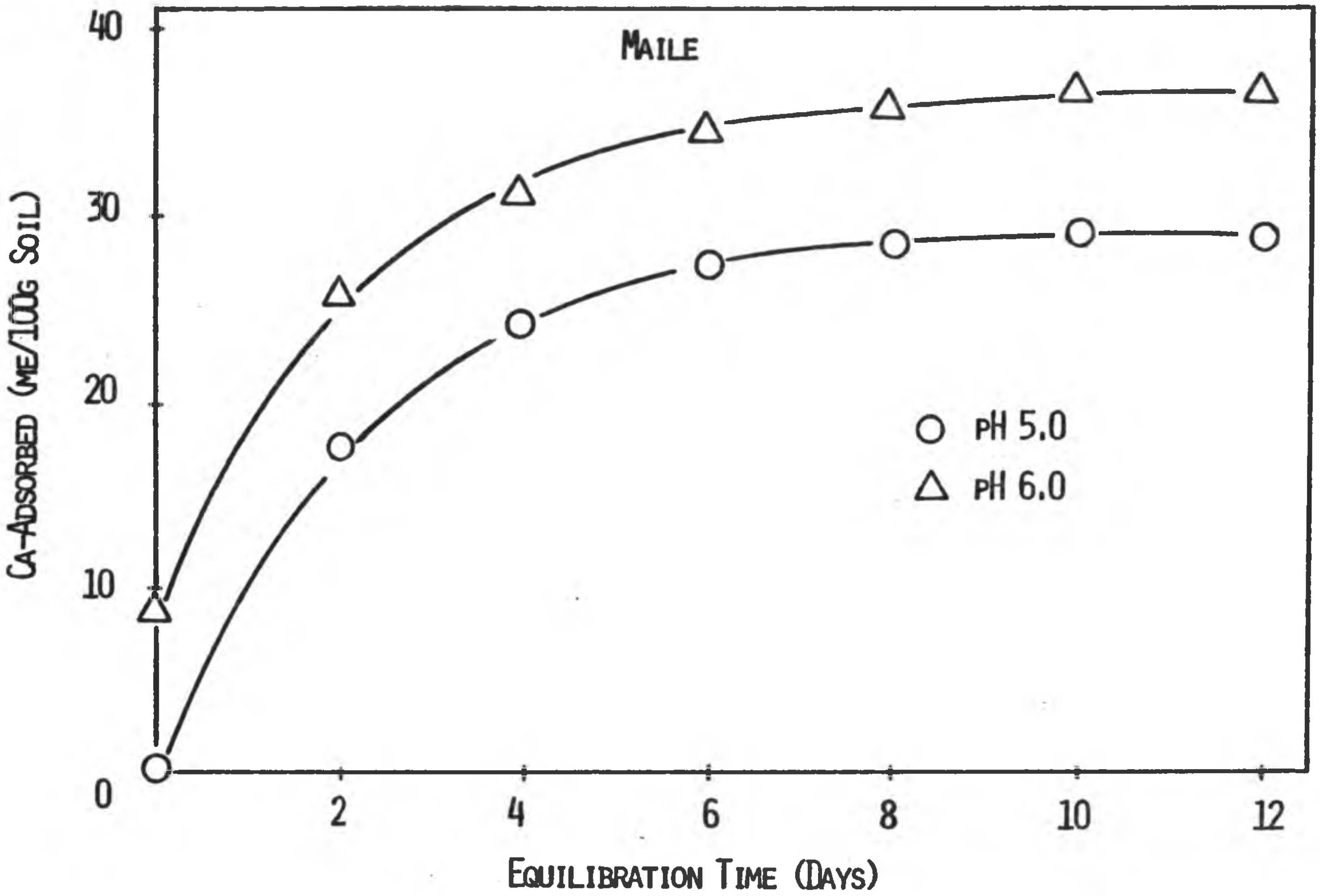

Fig. 6. Adsorption of Ca from 0.1 N calcium chloride solution.

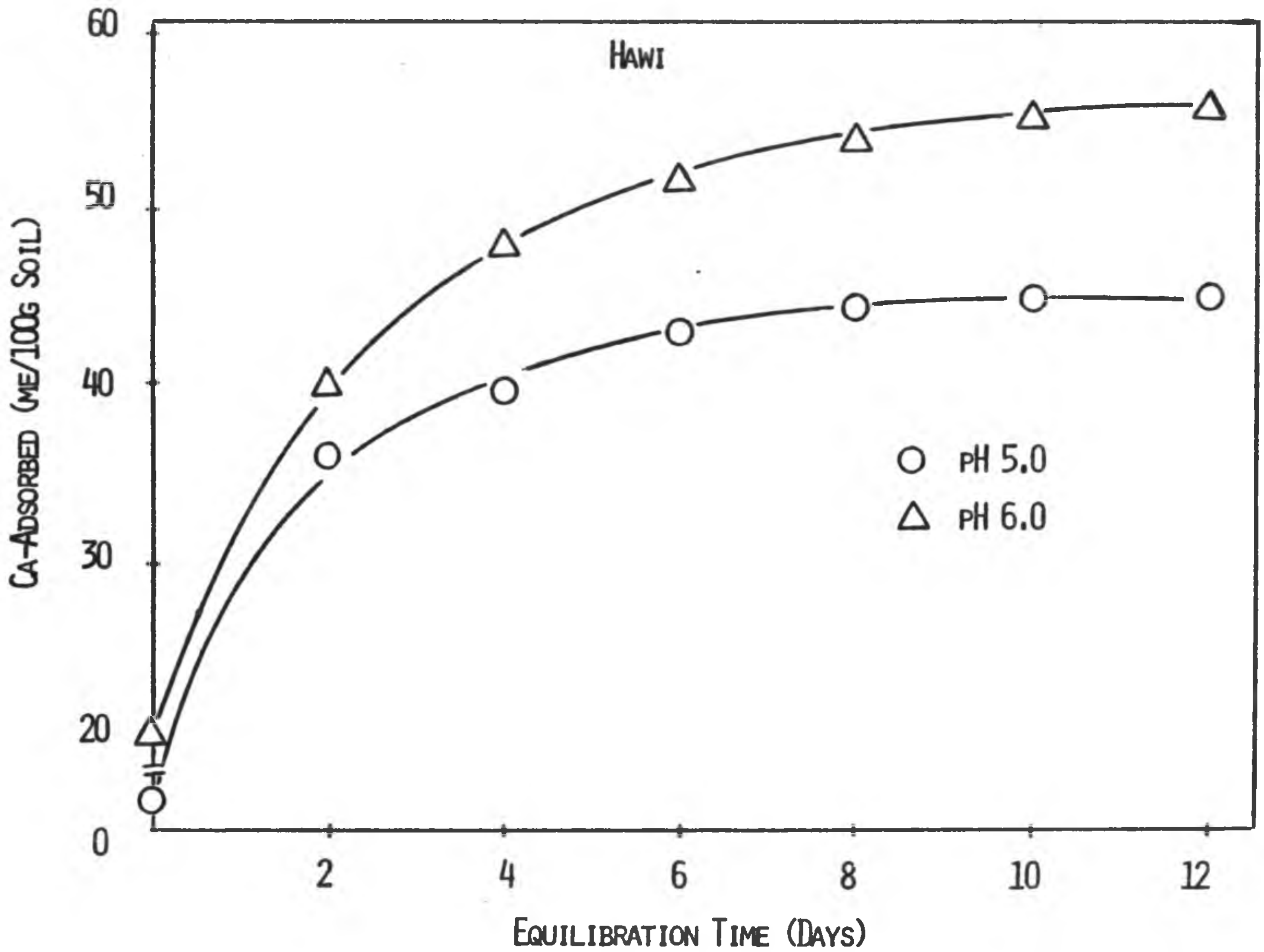

Fig. 7. Adsorption of Ca from 0.1 N calcium chloride solution.

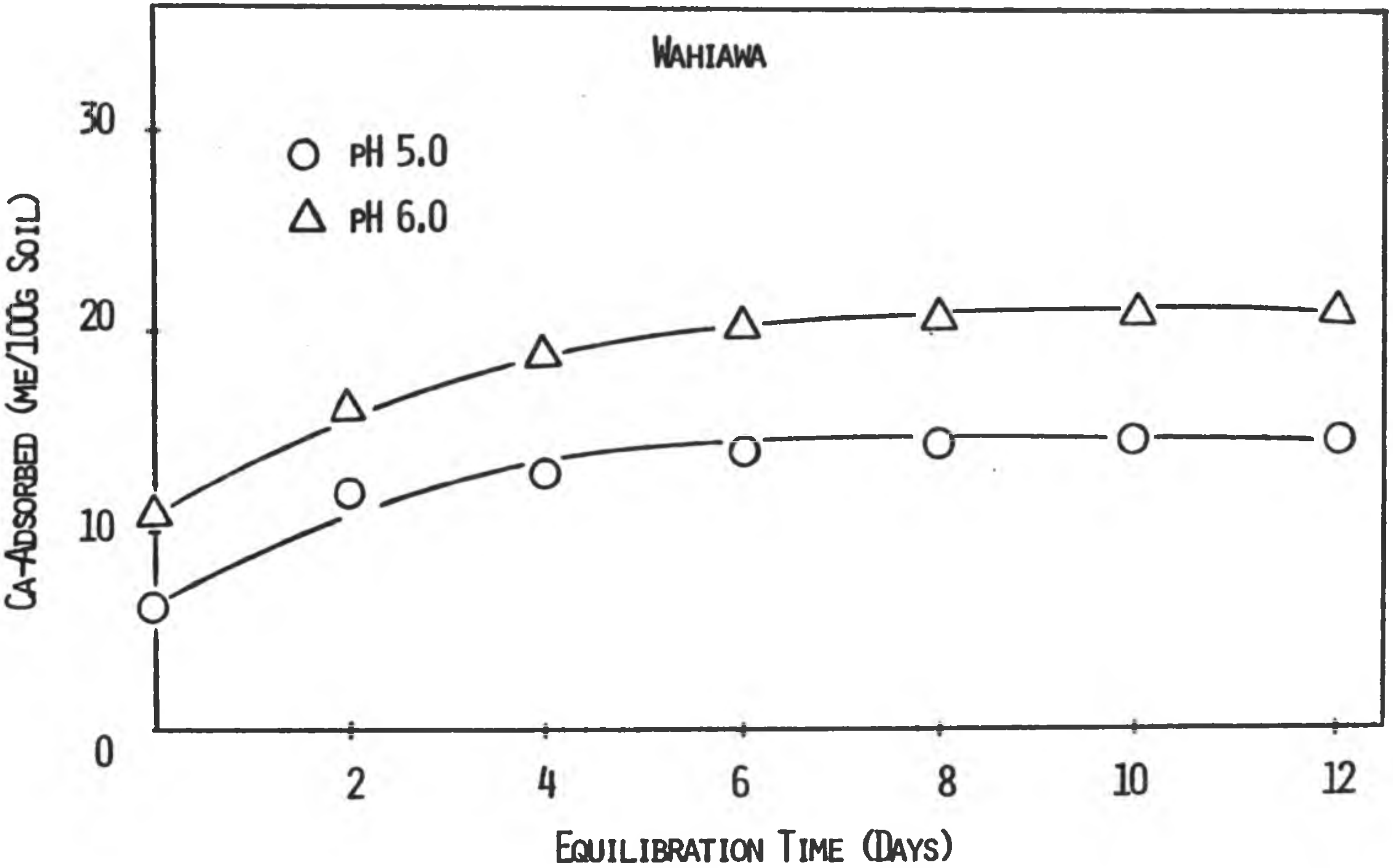

Fig. 8. Adsorption of Ca from 0.1 N calcium chloride solution.

Adsorption of Mg from 0.1 N magnesium chloride

The adsorption of Mg from 0.1 N magnesium chloride solution by the Maile, Hawi and Wahiawa (A) soils are shown in Figs. 9, 10 and 11, respectively. Ten days or less were required to bring about an equilibrium; however, in the case of Wahiawa (A) soil, a much shorter period of time was needed (6-8 days). Again, more Mg was adsorbed at pH 6.0 than at 5.0. The amount of Mg adsorbed by the three soils was between those of Ca and K at each corresponding pH level.

The amount of K, Ca and Mg adsorbed by the three soils at equilibrium with their chloride solutions (0.1 N) is summarized in Table 8. In general, In all soils at both pH levels, the quantity of adsorbed cations was in the following order:

$$Ca > Mg > K$$

Electrostatically, soil exists in equilibrium in which all negative charges and positive charges on the surfaces are neutralized by counter ions. The above trend would therefore illustrate the replacing power among these cations. For example, the initial base saturation of the Hawi soil is rather high (Table 3); however, the K adsorbed by the Hawi soil at the end of the equilibration with 0.1 N KCl solution is much lower than the corresponding cases of Ca and Mg, thus reflecting that K in the equilibrating solution is not very capable of completely replacing the

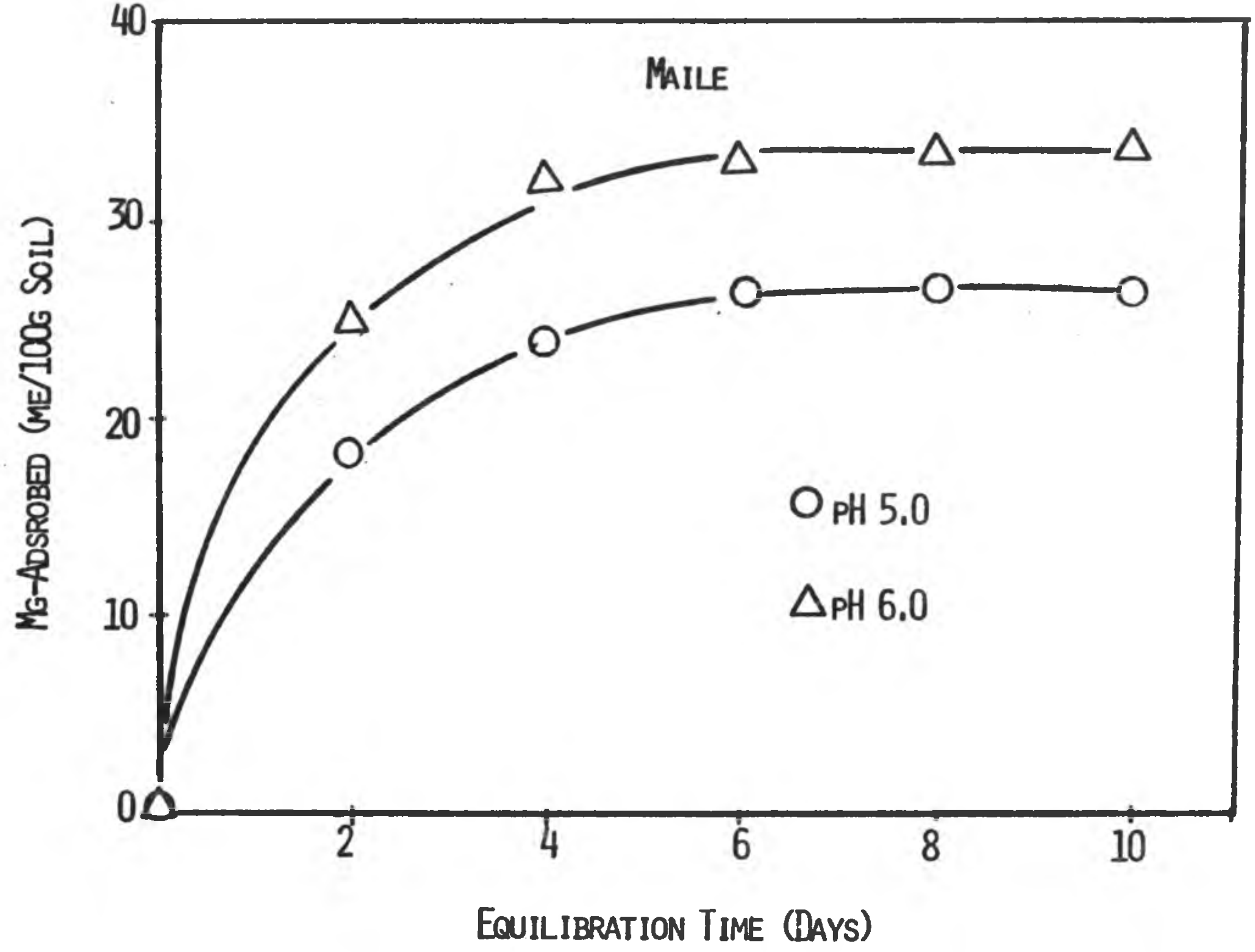

Fig. 9. Adsorption of Mg from 0.1 N magnesium chloride solution.

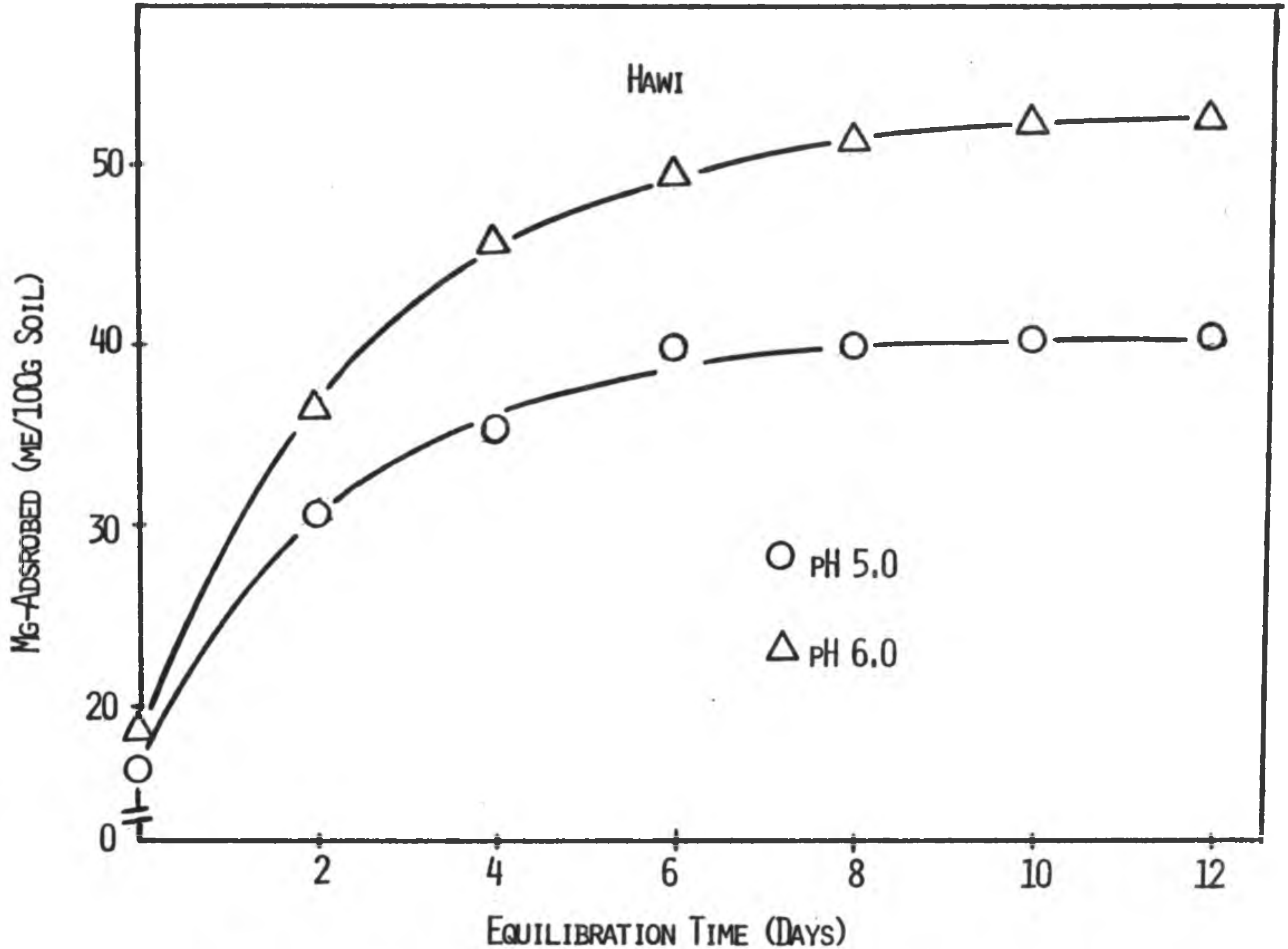

Fig. 10. Adsorption of Mg from 0.1 N magnesium chloride solution.

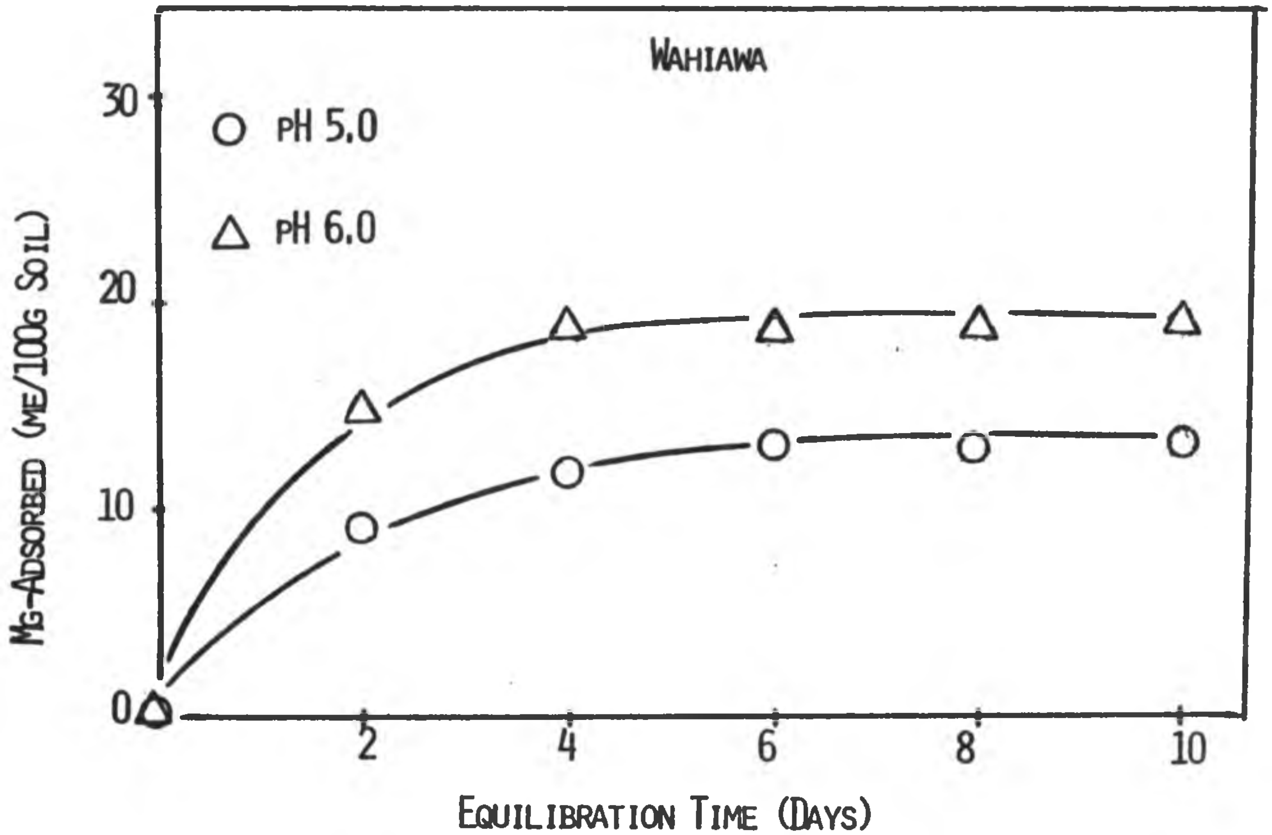

Fig. 11. Adsorption of Mg from 0.1 N magnesium chloride solution.

Table 8. Adsorption of K, Ca and Mg by soils from their corresponding chloride solutions (0.1 N), at two pH levels.

Soil	pH	Cation Adsorbed K	Ca	Mg	CEC [a/]
		me/100g			
Maile	5.0	25.9	29.2	26.2	45.2
	6.0	33.1	36.3	33.1	51.3
Hawi	5.0	16.8	44.7	40.4	48.1
	6.0	33.6	55.9	52.3	51.3
Wahiawa	5.0	11.0	14.1	12.9	15.7
(A)	6.0	17.2	20.5	18.6	16.3

a/ CEC was determined by 1 N ammonium acetate solution adjusted to soil pH.

initially adsorbed cations such as Ca and Mg etc. Ravina and Gurovich (1977) also observed a similar situation in which the CEC of a number of Ca-saturated soils determined by using monovalent cations such as Li and K as replacing cations was significantly less than those when divalent cations (Mg and Ba) were employed.

Competitive adsorption between K and Ca

Once the time required for achieving the equilibrium was established for each cation in each soil, experiments for competitive adsorption were initiated.

Maile Soil

Competitive adsorption between K and Ca is presented in Fig. 12a. At pH 5.0, regardless of the cationic ratios in the equilibrating solution, all values of the separation factors, C, were less than unity, thus indicating that Ca is preferentially adsorbed over K. At pH 6.0, however, the situation is rather complicated. Potassium was slightly preferentially adsorbed over Ca when the cationic ratio (K:Ca) in the equilibrating solution changed from 1:8 to 1:2 and this was shown by the near unity values in the separation factor (C). When there was equal amount of K and Ca (equivalence basis) in the equilibrating solution, Ca was slightly preferentially adsorbed over K by this soil. The exchange isotherm which was constructed as an alternative approach to investigate this adsorption behavior of the Maile soil, is presented in

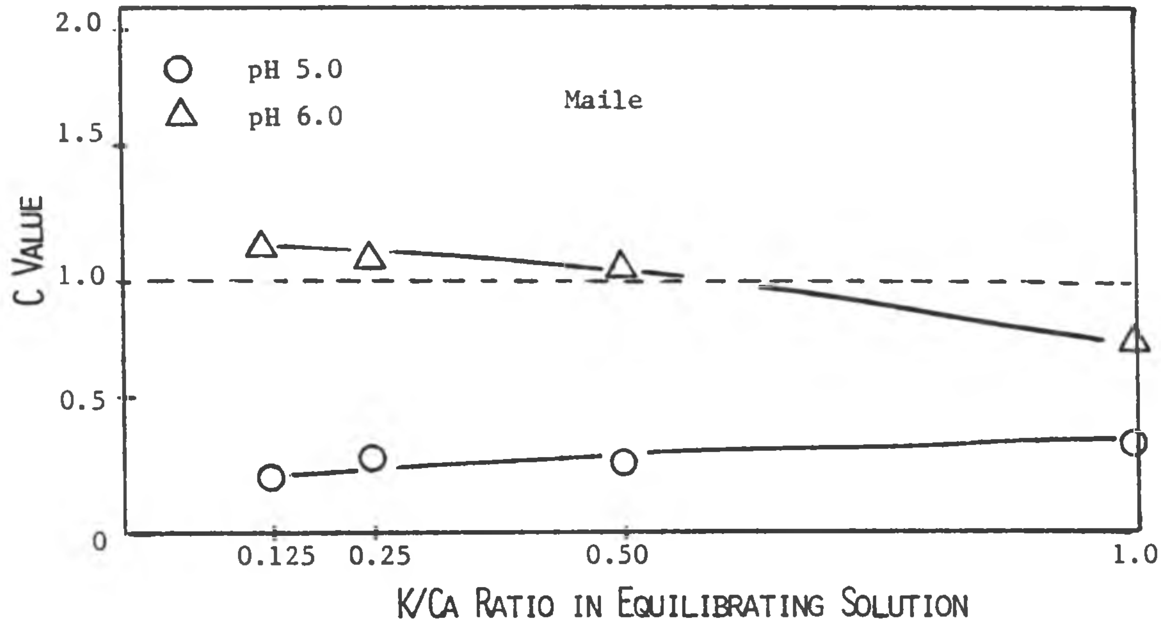

Fig. 12a. Competitive adsorption between K and Ca by Maile soil by the separation factor (C) approach.

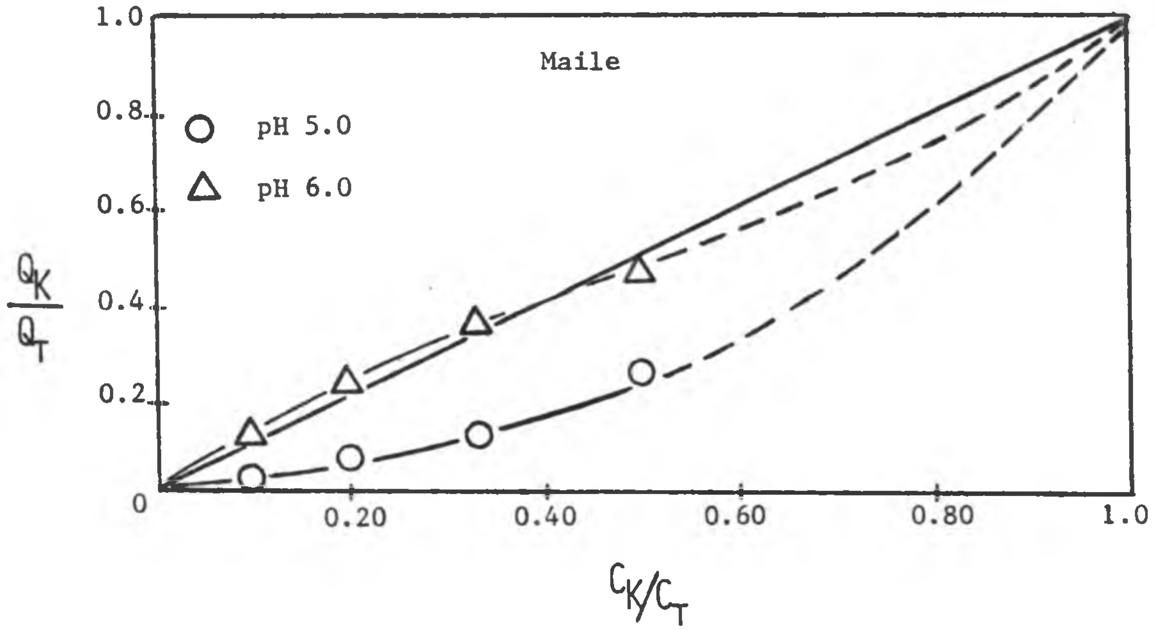

Fig. 12b. Competitive adsorption between K and Ca by Maile soil by the isotherm approach.

Fig. 12b, also illustrated a similar conclusion. It has been demonstrated outside the scope of this dissertation that the isotherm approach resulted in an identical conclusion as the one shown by the separation factor method; therefore, only the latter was used in the following description of the differential adsorption of K, Ca and Mg by the three soils at pH 5.0 and 6.0.

Hawi Soil

The differential adsorption of K and Ca by the Hawi soil is presented in Fig. 13. Regardless of pH levels as well as cationic ratios in the equilibrating solution, Ca was preferentially adsorbed over K by the soil colloids. The extent to which Ca was preferentially adsorbed was slightly greater at pH 5.0, as indicated by a lower separation factor (C) value at corresponding cationic ratio in the equilibrating solution, than at pH 6.0.

Wahiawa (A) Soil

At both pH levels and the four cationic ratios under investigation, all separation factor (C) values were greater than unity thus indicating that Wahiawa (A) soil adsorbs K preferentially over Ca although such a affinity was greater at pH 6.0 as shown by a much greater separation factor (C) values, than at pH 5.0 (Fig. 14).

Competitive adsorption between K and Mg

Maile Soil

The Maile soil preferentially adsorbed Mg over K at both pH 5.0 and 6.0 over the range of cationic ratio being

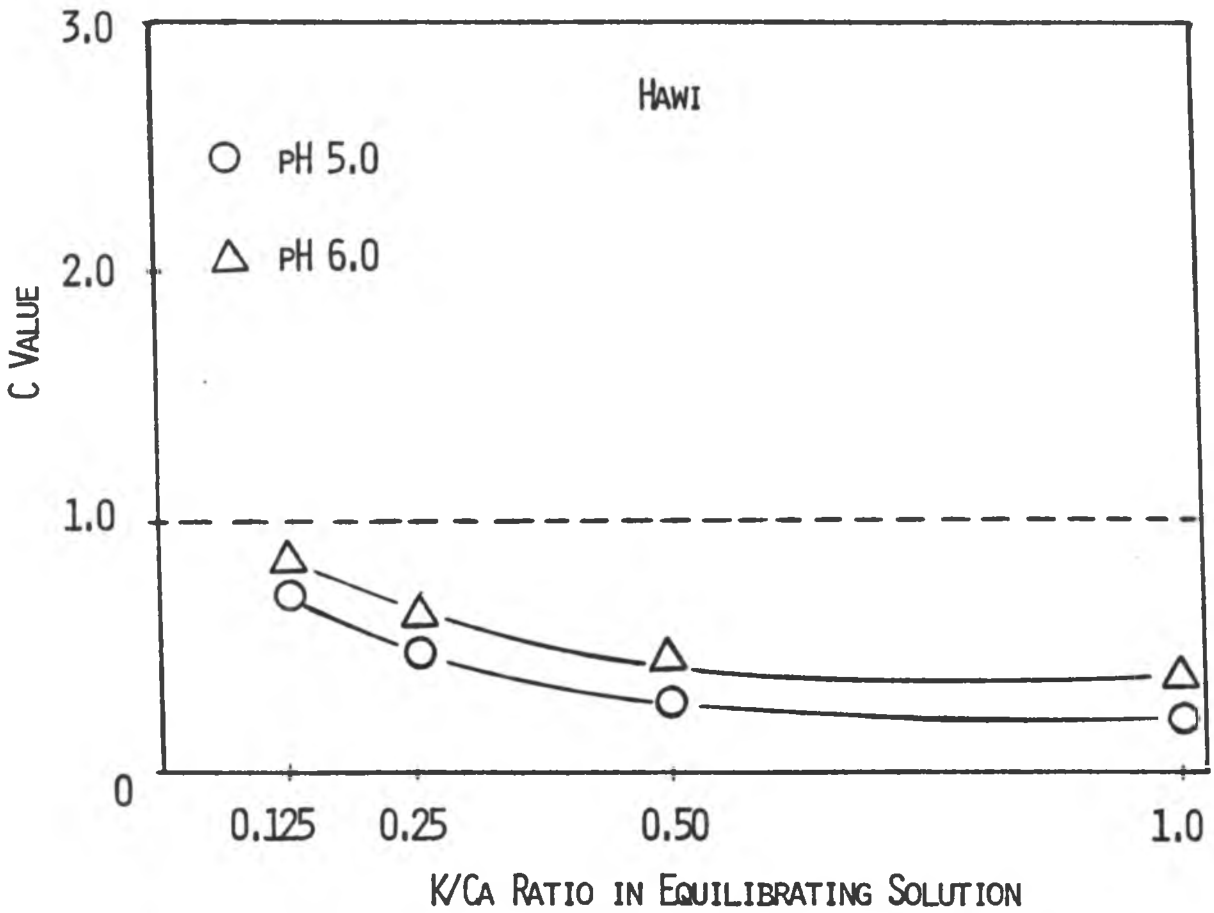

Fig. 13. Competitive adsorption between K and Ca by Hawi soil.

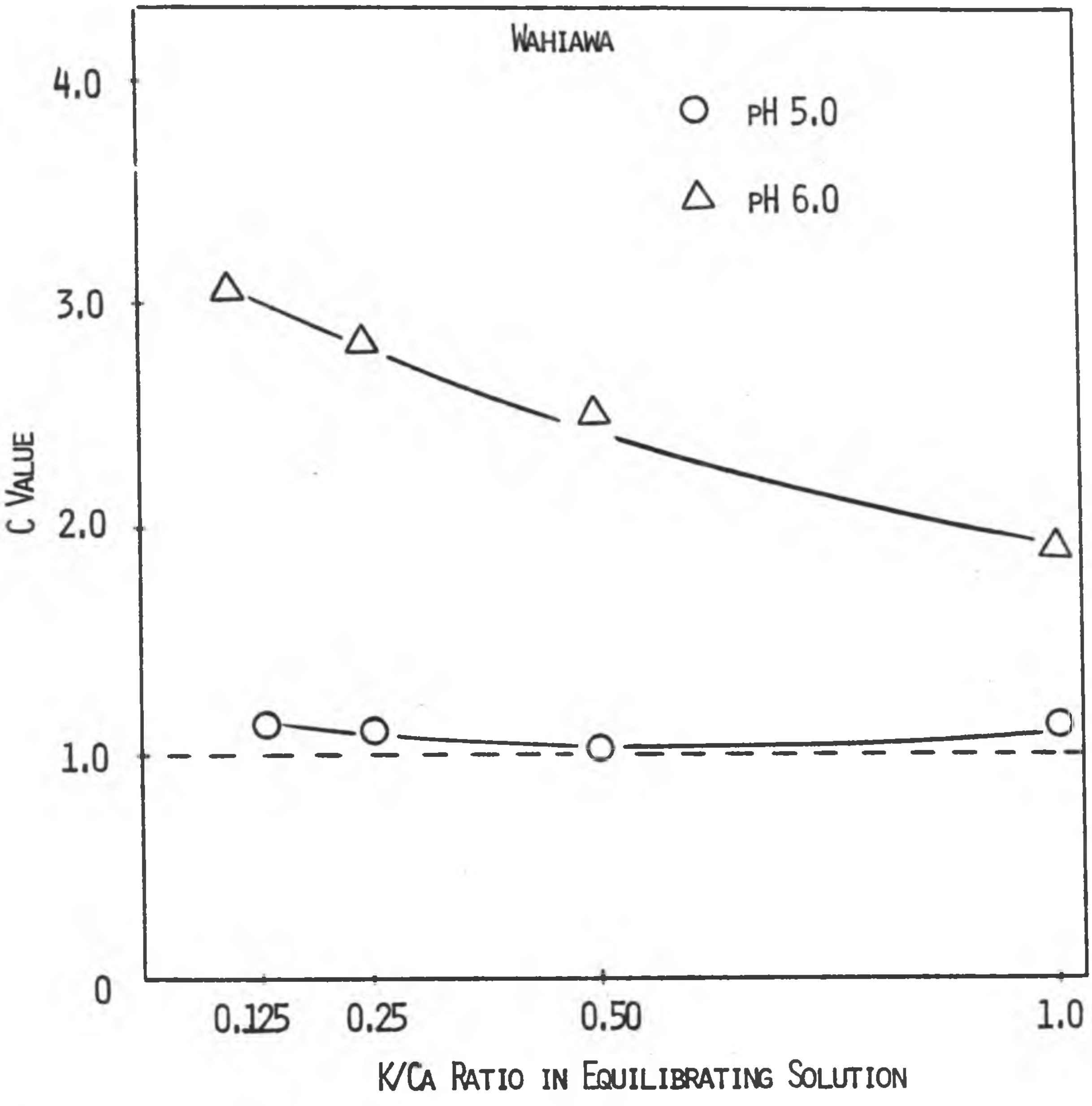

Fig. 14. Competitive adsorption between K and Ca by Wahiawa (A) soil.

studied in this investigation (Fig. 15). Two opposite trends were observed between the two pHs. At pH 5.0, preferential K adsorption was enhanced at the lower Mg fraction in the equilibrating solution. At pH 6.0, affinity for K adsorption decreased as Mg fraction decreased.

Hawi Soil

Except at the cationic ratio (K:Mg) of 1:8 at both pH levels where the soil showed no significant adsorption preference for either element, Hawi soil exhibited selective adsorption of Mg over K where the cationic ratio ranged from 1:4 to 1:1 (Fig. 16). Regardless of the pH, the separation factor (C) decreased with increasing cationic ratio (increasing fractional K) in the equilibrating solution, thus indicating that the affinity for Mg adsorption over K by this soil increased with increasing K fraction in the equilibrating solution.

Wahiawa (A) Soil

The Wahiawa (A) soil preferentially adsorbed K over Mg at pH 5.0. This held true at all K:Mg ratios in the equilibrating solution (Fig. 17). At pH 6.0, K was preferentially adsorbed over Mg at K:Mg solution ratios between 1:8 and 1:2, but when this ratio was 1:1, Mg was adsorbed preferentially to K. Wahiawa (A) soil exhibited stronger affinity for K than Mg although such an affinity decreased as the fractional K in equilibrating solutions increased.

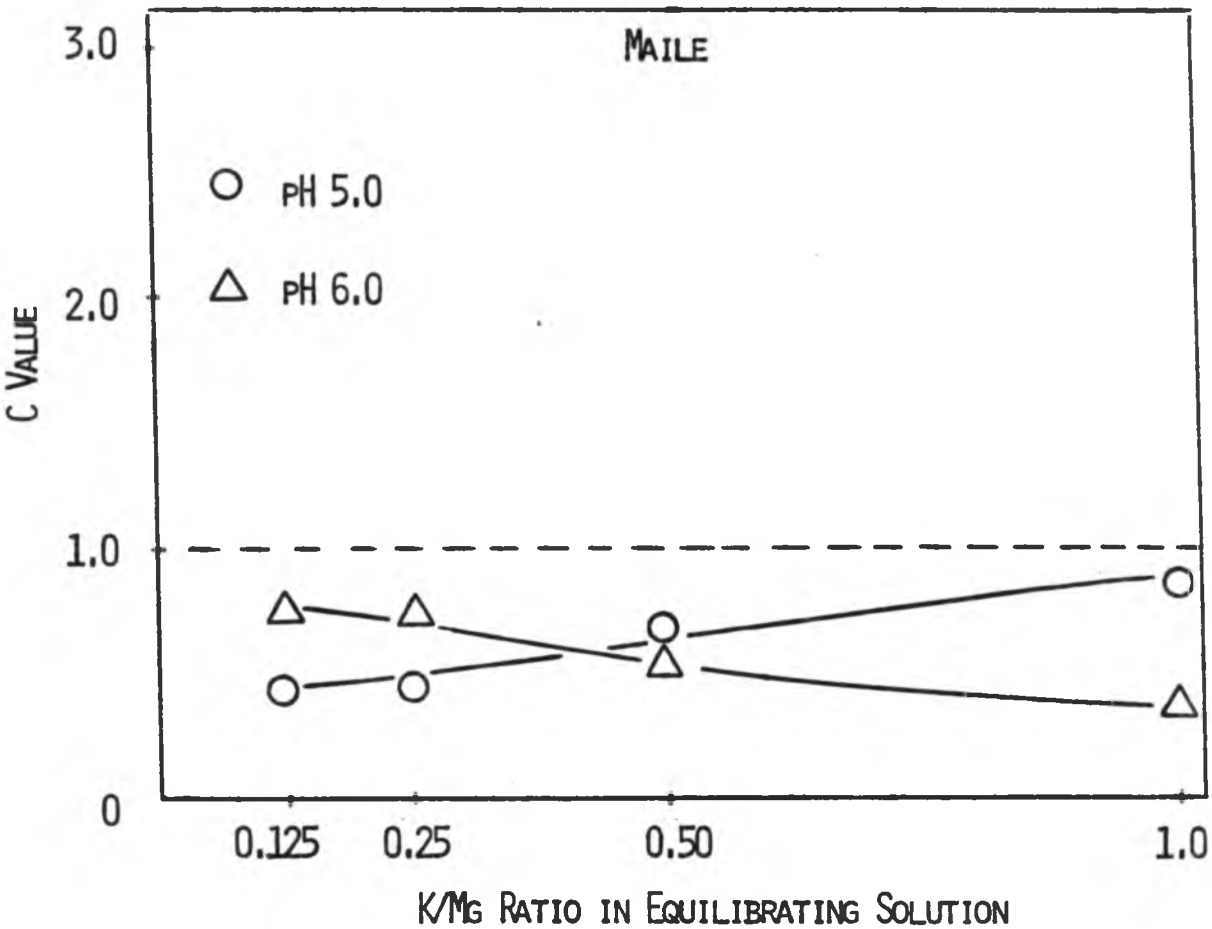

Fig. 15. Competitive adsorption between K and Mg by Maile soil.

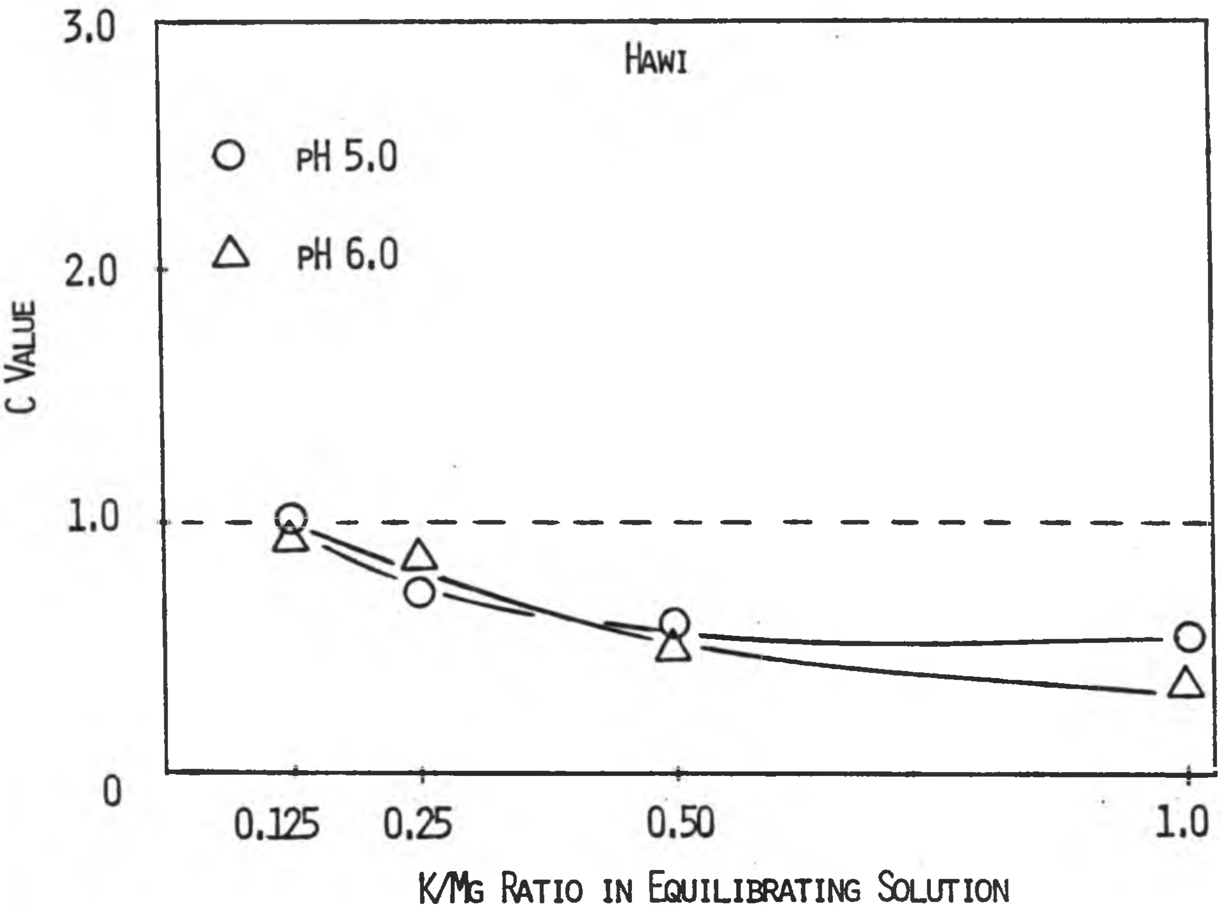

Fig. 16. Competitive adsorption between K and Mg by Hawi soil.

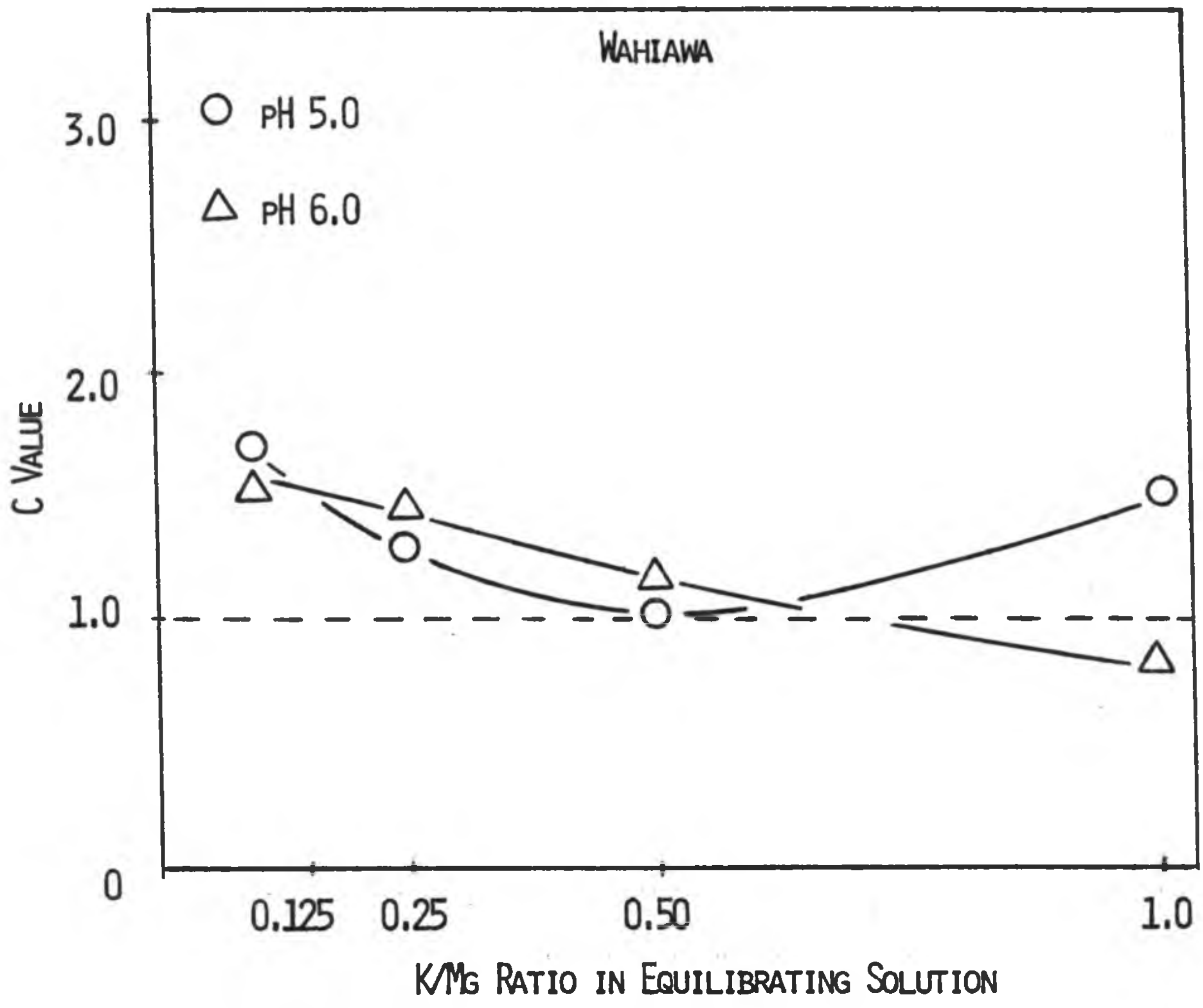

Fig. 17. Competitive adsorption between K and Mg by Wahiawa (A) soil.

Competitive adsorption between Mg And Ca

Maile Soil

The selective adsorption of Mg and Ca by the Maile soil is shown in Fig. 18. Regardless of pH levels, all separation factort (C) values are below unity, thus indicating that Maile soil preferentially adsorbed Ca over Mg The affinity for Ca over Mg by the Maile soil decreased as the cationic ratio (Mg:Ca) in the equilibrating solution approached unity. In general, the soil shows a stronger affinity for Ca over Mg at pH 5.0, as indicated by a relatively smaller C values, than at pH 6.0.

Hawi Soil

At pH 5.0 and 6.0, the separation factor (C) values are less than unity which indicates that Hawi soil adsorbed Ca preferentially over Mg (Fig. 19). The variation in the degree of such an adsorption between the two pHs was not significantly different although values of the separation factor (C) at pH 5.0 appear to be slightly greater than the corresponding one at pH 6.0.

Wahiawa (A) Soil

The change of the separation factor (C) in response to various levels of cationic ratios (Mg:Ca) in the equilibrating solution for Wahiawa (A) is shown in Fig. 20. Wahiawa (A) soil preferred Ca over Mg at both pH levels, although its affinity for Ca over Mg was stronger at pH 5.0 than at 6.0. At the same time, the C values decreased

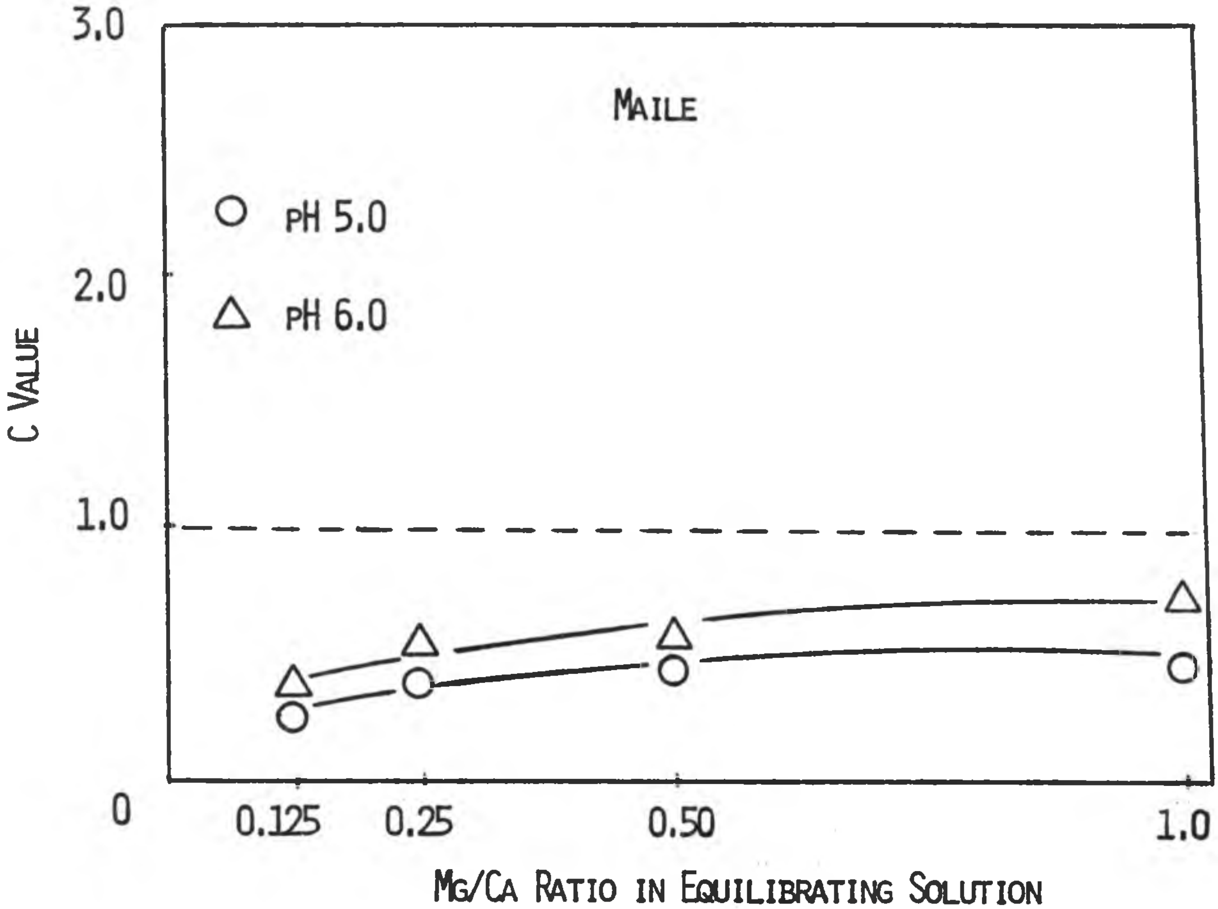

Fig. 18. Competitive adsorption between Mg and Ca by Maile soil.

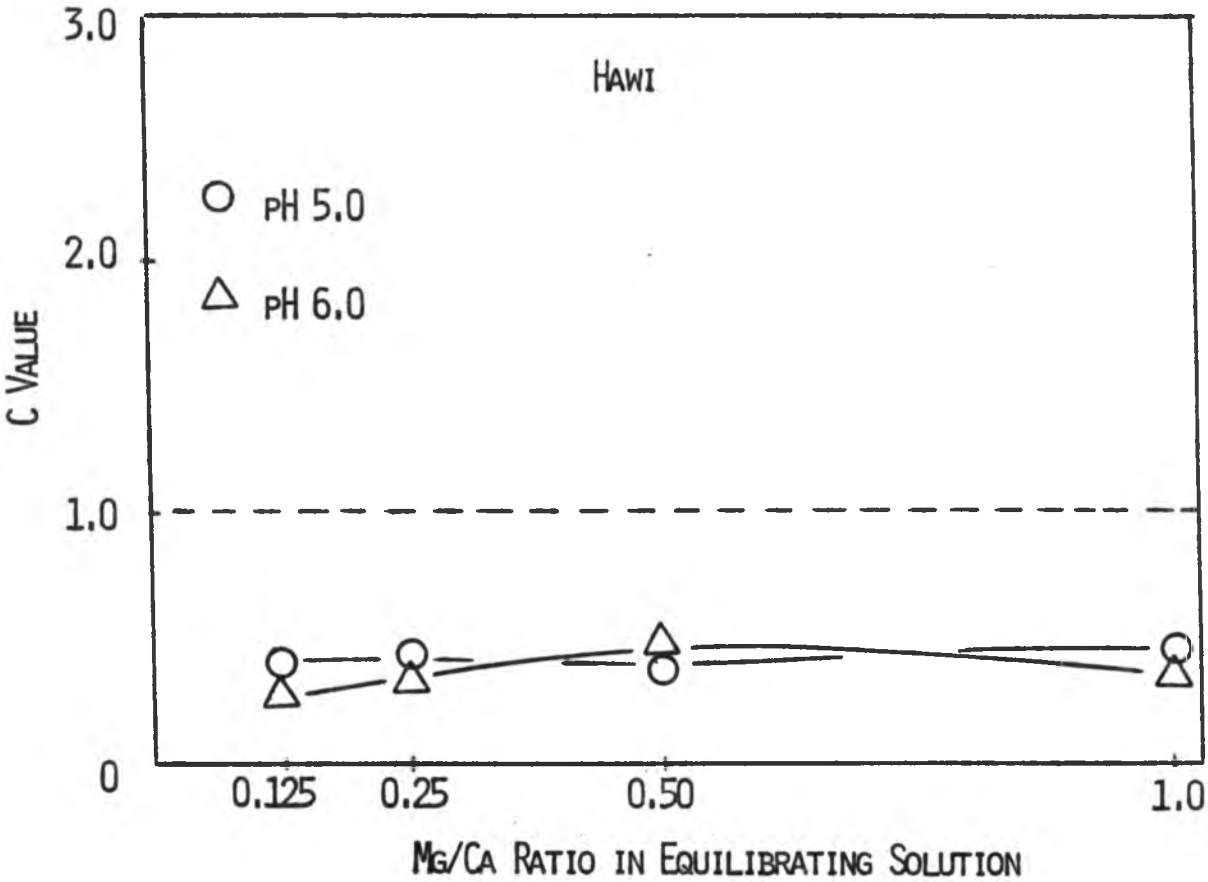

Fig. 19. Competitive adsorption between Mg and Ca by Hawi soil.

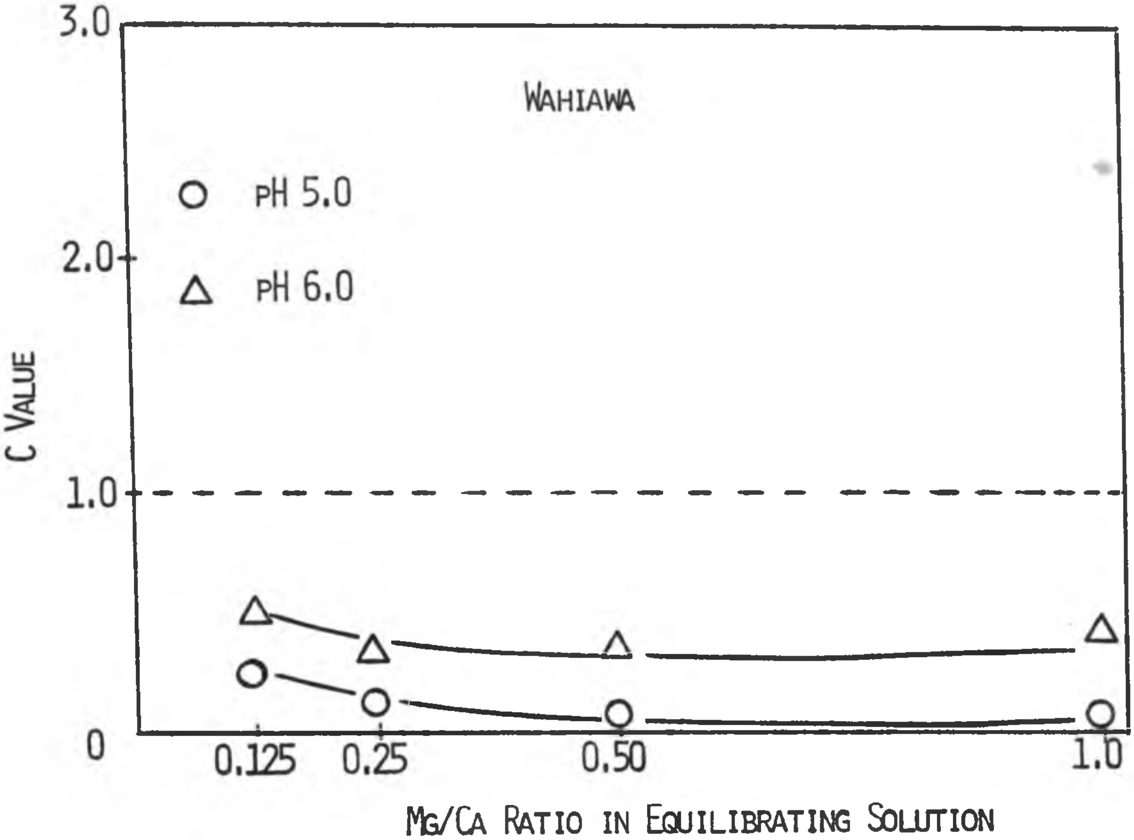

Fig. 20. Competitive adsorption between Mg and Ca by Wahiawa (A) soil.

progressively with increasing cationic ratio at pH 5.0, thus reflecting that such affinity tends to be stronger as more Ca is incorporated into the equilibrating solution; in fact, at a cationic ratio of Mg:Ca 0.5 or higher, Wahiawa (A) soil predominately adsorbed Ca over Mg as indicated by a very low value of C, ie. 0.07 at both Mg:Ca=0.5 and Mg:Ca=1.0.

In general, the differential adsorption of K, Ca and Mg by the three soils at both pH levels were in the following order:

Maile	Ca > Mg > K
Hawi	Ca > Mg > K
Wahiawa (A)	K > Ca > Mg

The preference for divalent cations, such as Ca and Mg over monovalent cations, by both Maile and Hawi soils, is not surprising. Mattson (1948) and Wiklander (1946), with the aid of the Donnan Equation, dveloped the theory that materials with high cation exchange capacity (CEC) would retain divalent cations with stronger bonding energies than monovalent cations; hence such a system tends to release its monovalent cations more readily than its divalent cations. The above concepts seem to fit these two soils since they have a relatively high CEC as determined by 1 N ammonium acetate method. If the adsorption force between the soil surface and the counter ions is electrostatic in nature, it can be predicted, based on the

Coulomb's theory, that divalent cations are held with greater energy than monovalent cations. At the same time, the high organic matter in these two soils (Table 3.) may also influence the selective retention of cations. It has been suggested by some scientists that the retention of cations by organic matter involves "specific adsorption" leading to the formation of complexes with various organo-metallic stability constants (Mangaro et al, 1965; Stevenson, 1976; El-Sayed et al 1970). Schachschabel (1940) concluded that clay minerals with a high humic acid level, soft coal (Kasselerbraun) and soil humic matter had strong adsorption of divalent cations as compared with monovalent cations. He also reported that up to 92% of the Ca in the leaching solution composed of 0.05 N calcium acetate and ammonium acetate, respectively, was adsorbed by humic matter while only 5-6% of it was adsorbed by biotite, 56-63% by montmorillonite, 54% by kaolinite and 19% by feldspar. Beaver and Hall (1937) observed that the easiness of cations to be incorporated into humic acid was in the order of:

$$Ba > Ca > Mg > Sr > K > Na > Li$$

Within Group 2 elements, in general, Ca is often preferentially adsorbed over Mg by soil. Schnitzer and Skinner (1966) studied the specific adsorption of some metal ions onto fulvic acid derived from a podzol Bh horizon at both pH 3.5 and 5.0. They reported that the stability of the complex or binding strength for Ca was greater than that for Mg; this in turn reflected that Ca was held with higher bond energy by fulvic acid as compared to Mg. Apart from the role of soil organic matter in the selective adsorption of these two cations (specific adsorption), the non-specific adsorption (electrostatic force) also offers an explanation of the preferential adsorption of Ca over Mg. If the bonding force in the adsorption process is electrostatic in nature, ion with the smallest hydrated radius will be able to approach the adsorption site more closely and therefore be held more strongly according to the Coulomb's Law. Since the hydration radius of Ca is 4.12 A while that of Mg is 4.28 A (Nightingale, 1959), the smaller hydrated Ca would therefore be adsorbed with greater energy on the soil surface than the slightly larger hydrated Mg cation.

Several mechanisms may be responsible for the preferential adsorption of K over Ca and Mg by the Wahiawa (A) soil. Firstly, the mineralogical analysis of Wahiawa (A) soil by X-ray diffraction reveals the presence of mica, illite and kaolinitic materials (5%, 12% and 15%, respectively, Table 2). Mica and illite type minerals are characterized by having internal negative charges which attract cations onto internal surfaces between the respective silica sheets. Potassium ions, which has just the right size to fit into such cavities, hence become trapped as part of the rigid crystal structure. Such "potassium fixation" mechanism by mica and illite type materials is widely reported by many investigators (Wood and DeTurk, 1941; Bray and DeTurk, 1939; Stanford, 1947). Volk (1938) showed that K fixation was accompanied by the formation of mica. Wiklander (1946) indicated that K was bound with much greater energy by kaolin than by montmorillonite. By using the Donnan theory, Mattson (1948) and Wiklander (1946) predicted that kaolinite, being with lower CEC value, adsorbed K with greater bonding energy than divalent cations such as Ca and Mg. More recently, Jensen (1973) and Udo (1978) attributed the preferential adsorption of K by kaolinite to the specific interactions of the cation with the edge sites of this mineral. Pleysier et al (1979) demonstrated in a kaolinitic Ultisol that K was selectively adsrobed over Ca when Al was not involved in the equilibrating process.

Secondly, significant amount of anion exchange capacity may be possessed by some tropical soils at low pH, especially those with oxidic mineralogy. Carrasco (1972) and van Raij and Peech (1972) obtained less than 1 me/100g of AEC (of anion exchange capacity) in an Ultisol, Oxisol and Alfisol. The presence of such positive charges on the soil colloidal surfaces tend to repel polyvalent cations more strongly than monovalent ones; therefore the accessibility to the soil colloidal surfaces for adsorption will be much easier for the monovalent K than both of the divalent Ca and Mg.

Thirdly, the degree of hydration among these cations on Wahiawa (A) soil affects its selective adsorption behavior. Hendrick et al (1941) advocated that K might not be hydrated at all. The degree of hydration as well as the energy of hydration per water molecule, as reported by Hutcheon (1966), was greater for Ca than K. Deist and Talibudeen (1967) concluded that the preferential adsorption of K over Ca was due to the greater degree of hydration of Ca (hence, larger hydration radius) than K; therefore, Ca would be further away because of steric effect from the adsorption sites than K. Potassium, with an effective hydrated radius of 3.31 A while those of calcium and magnesium are 4.12 A and 4.28 A, respectively (Nightingale, 1959), would therefore be adsorbed more strongly than Ca or Mg on the adsorption sites of the soil. This situation also occurs in both Maile and Hawi soils; however, the enormous effect exerted by the organic matter on the selective adsorption of divalent over monovalent cations in these two soils overcome the above phenomenon in such a way that its contribution to the adsorption process was undoubtfully masked.

Hence, the selective adsorption of one ion over the other by a particular soil is a function of the valency of the ion, its degree of hydration, presence or absence of organic matter, soil pH, ratio among ions in soil solution as well as the characteristics of the clay minerals of the soil. The algebraic sum of all these factors determines the preferential adsorption of a particular ion over the other onto the adsorption sites of a certain soil.

Effect of K, Ca and Mg Fertilizers on Yield, Mineral Content and Grass Tetany Ratio of Kikuyugrass (*Pennisetum clandestinum* Hochst. ex Chiov.) Grown on Two Tropical Soils at Two pH Levels

The effect of applied K, Ca and Mg fertilizers and their combinations on dry matter yield of kikuyugrass

Dry matter yield increased significantly by increasing rates of K applications in both Maile and Wahiawa (B) soils at pH 5.0 and 6.0 (Fig. 21). Data reported is total yield of four consecutive harvests. This is consistent with data of a field study on the effect of N, P and K rates on the yield of kikuyugrass by Tamimi et al (1976). At the same time. Dry matter yield at pH 6.0 was greater than that of pH 5.0 which might be due to the higher level of K, Ca and Mg and/or the reduction of the toxic Al and Mn in both soils at the elevated pH level. Azmi et al (1976) observed that the dry matter yield of kikuyugrass was increased by raising the soil pH from 4.19 to 6.12 and they concluded that such an increase was due to the improved Ca nutrition as well as the reduction of toxic Al

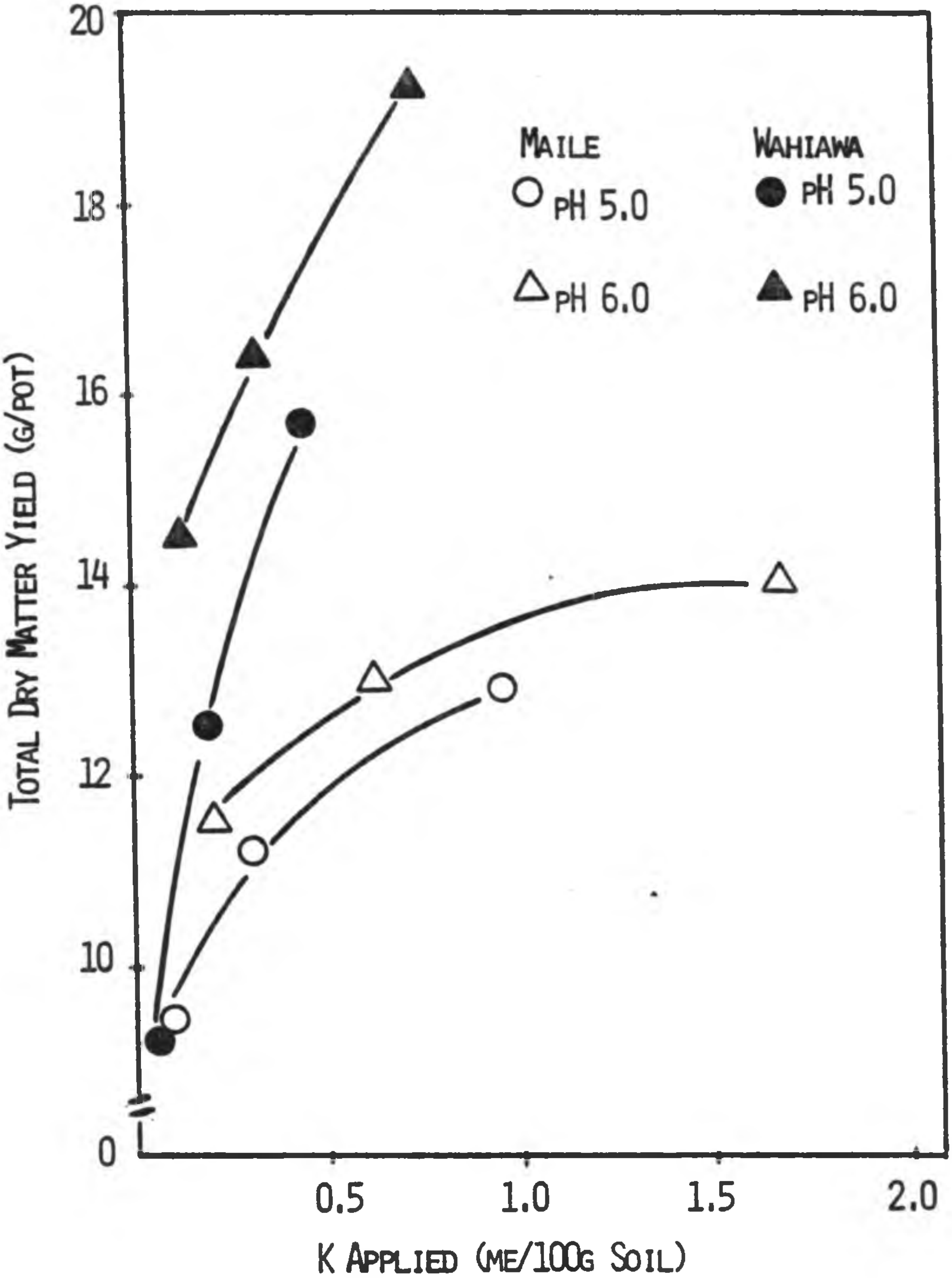

Fig. 21. Effect of applied K on total dry matter yield of kikuyugrass.

in the soil. In fact, the Mn concentration of tops of the kikuyugrass harvested from both soils in this study was higher at pH 5.0 than at 6.0 (Table 9) thus reflecting that the increase in dry matter yield at the elevated pH level was partially due to the reduction of the toxic Mn in soil. The total dry matter yield of kikuyugrass grown in Wahiawa (B) soil was much greater than that grown in Maile soil at corresponding pH levels (Fig. 21). This may be due to the four times as much soil per pot was used for Wahiawa (B) than Maile soil (2000g vs. 500g) due to their differences in bulk density; hence greater amounts of nutrients (quantitative basis) were associated with the former than the latter soil. It is also possible that soil P level for optimium production of kikuyugrass was not achieved in the Maile soil as compared to that in the Wahiawa (B) soil (Table 10). The relationship between dry matter yield and tissue K concentration for kikuyugrass grown in Maile soil is shown in Fig. 22. The regression equation obtained demonstrates that the maximium yield was associated with a tissue K content of 3.8%. In the case of Wahiawa (B) soil (Fig. 23), tissue K content associated with maximum yield could not be determined since the maximium yield was not attained by the rates applied; however, a very highly significant linear correlation existed between these two parameters (R=0.63**).

Table 9. Effect of soil pH on Mn concentration in kikuyugrass grown in Maile and Wahiawa (B) soils at pH 5.0 and pH 6.0.

	Tissue Mn (ppm)	
Soil pH	Maile	Wahiawa (B)
5.0	134a a/	1405a
6.0	96b	429b
	**	**

a/ Means in the same column followed by the same letter are not significantly different at 5% level determined by Duncan Multiple Range Test.

Table 10. Extractable P in Maile and Wahiawa (B) soils at pH 5.0 and pH 6.0 at the end of the study.

Soil	Extractable P (ppm) pH 5.0	pH 6.0
Maile	25.3	25.2
Wahiawa (B)	307	323

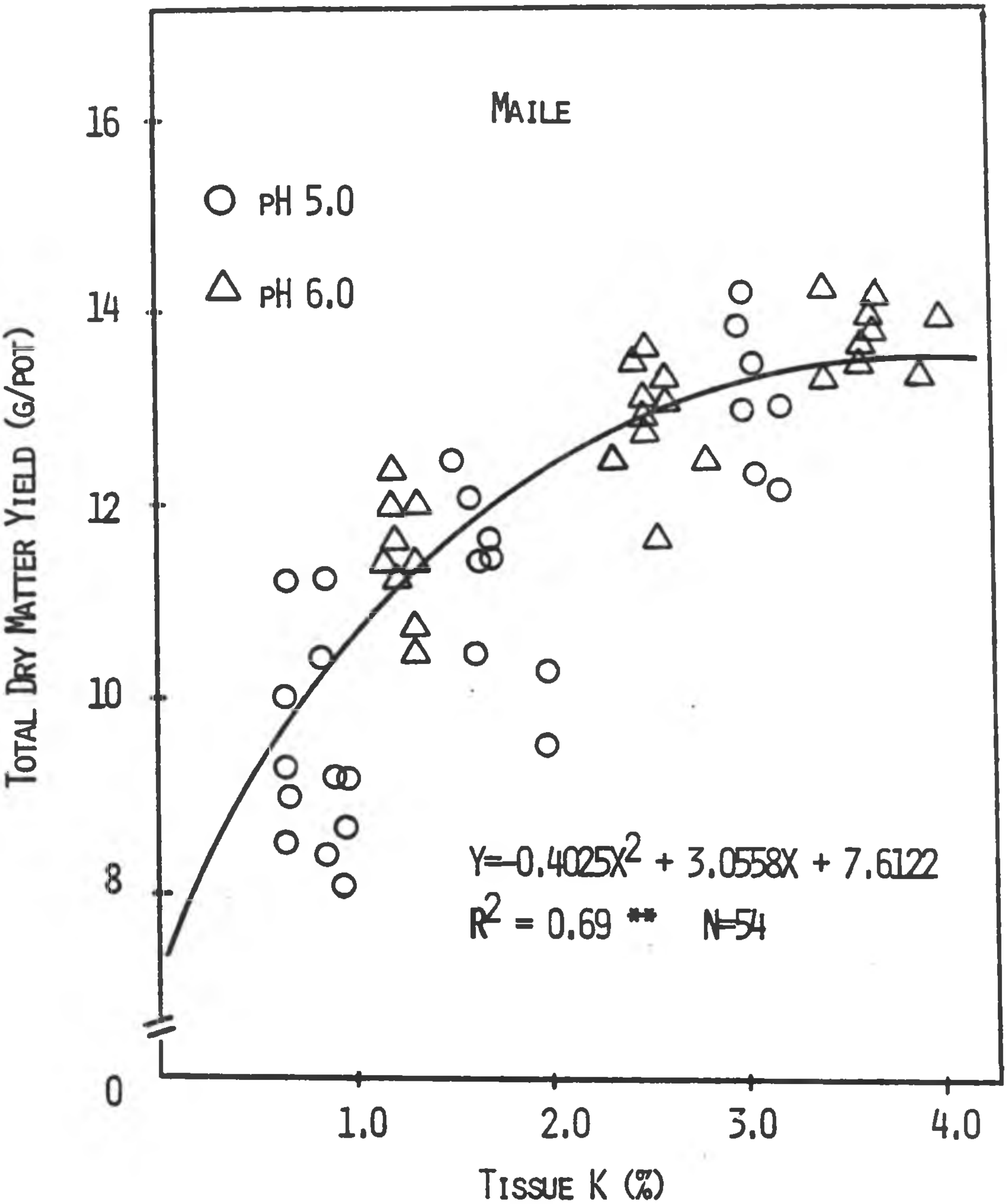

Fig. 22. Relationship between tissue K concentration and dry matter yield of kikuyugrass grown in Maile soil.

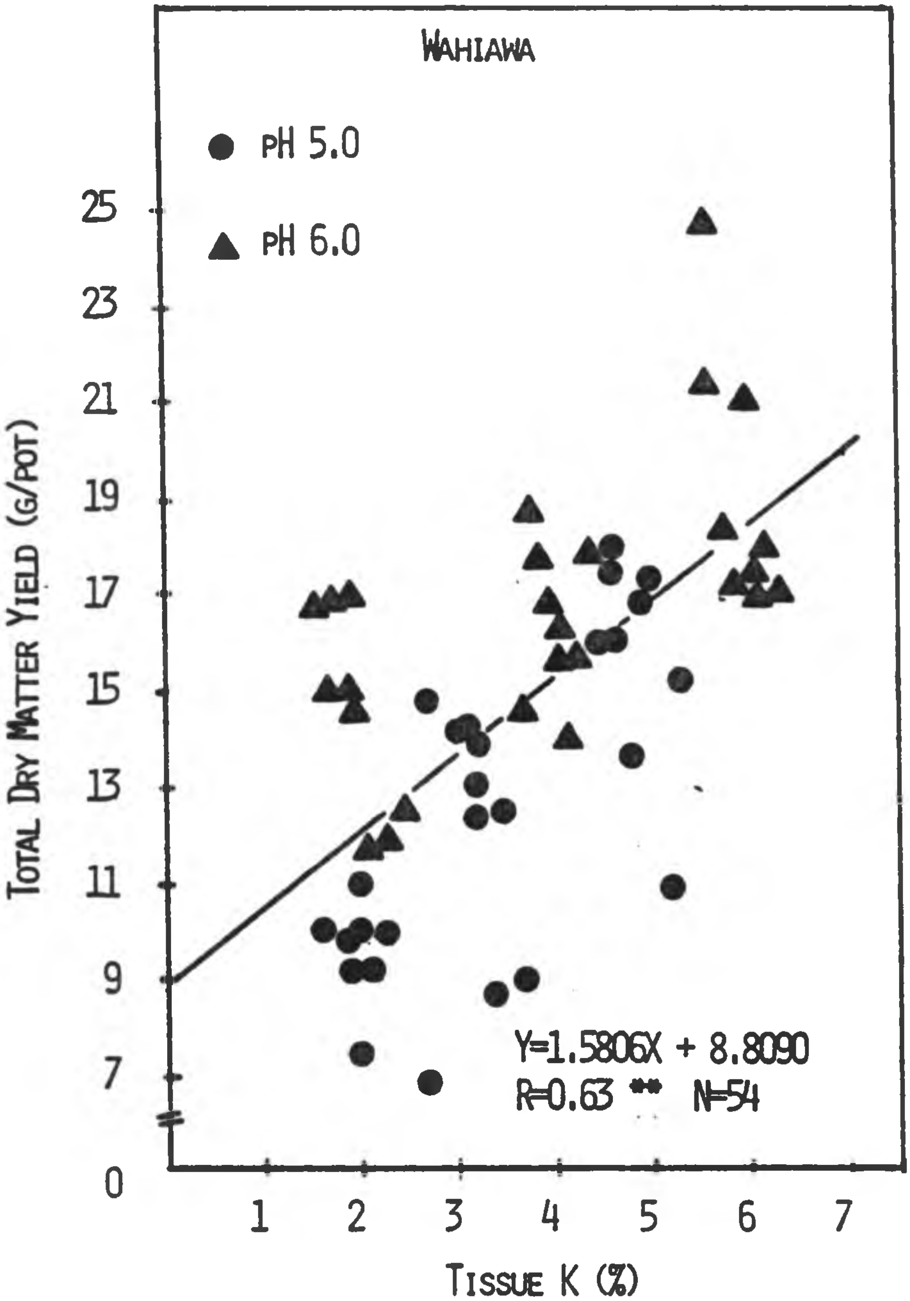

Fig. 23. Relationship between tissue K concentration and dry matter yield of kikuyugrass grown in Wahiawa soil.

The total dry matter yield of kikuyugrass per pot as affected by Ca applied in both soils is shown is Fig. 24. In the Maile soil, total dry matter yield was not affected by various levels of applied Ca at both pH levels though greater yield was obtained at pH 6.0 than at pH 5.0. In the case of Wahiawa (B) soil, the total dry matter yield increased significantly by increasing applied Ca at both soil pH levels, and significantly greater dry matter yield was achieved at pH 6.0 than at 5.0. Unlike the Maile soil where the higher dry matter yield at pH 6.0 than at 5.0 was brought about by the pH effect only, such response in Wahiawa (B) soil resulted from both soil pH and increasing rate of applied Ca. In a solution culture experiment, Cassidy (1972) observed that the dry matter yield of kikuyugrass was higher in the presence of Ca than in its absence. Azmi et al (1972) suggested that the dry matter yield kikuyugrass was severely restricted when the Ca concentration of tops was less than 0.11%. Tamimi et al (1971) also obtained an increase in the dry matter yield of kikuyugrass upon liming though they did not specify if such response was due to the improved Ca nutrition or the reduction of the toxic elements such as Al and Mn in soil.

The response of the total dry matter yield of kikuyugrass to applied Mg in both Maile and Wahiawa (B) soils is presented in Fig. 25. Total dry matter production of kikuyugrass in Maile soil increased with increasing soil

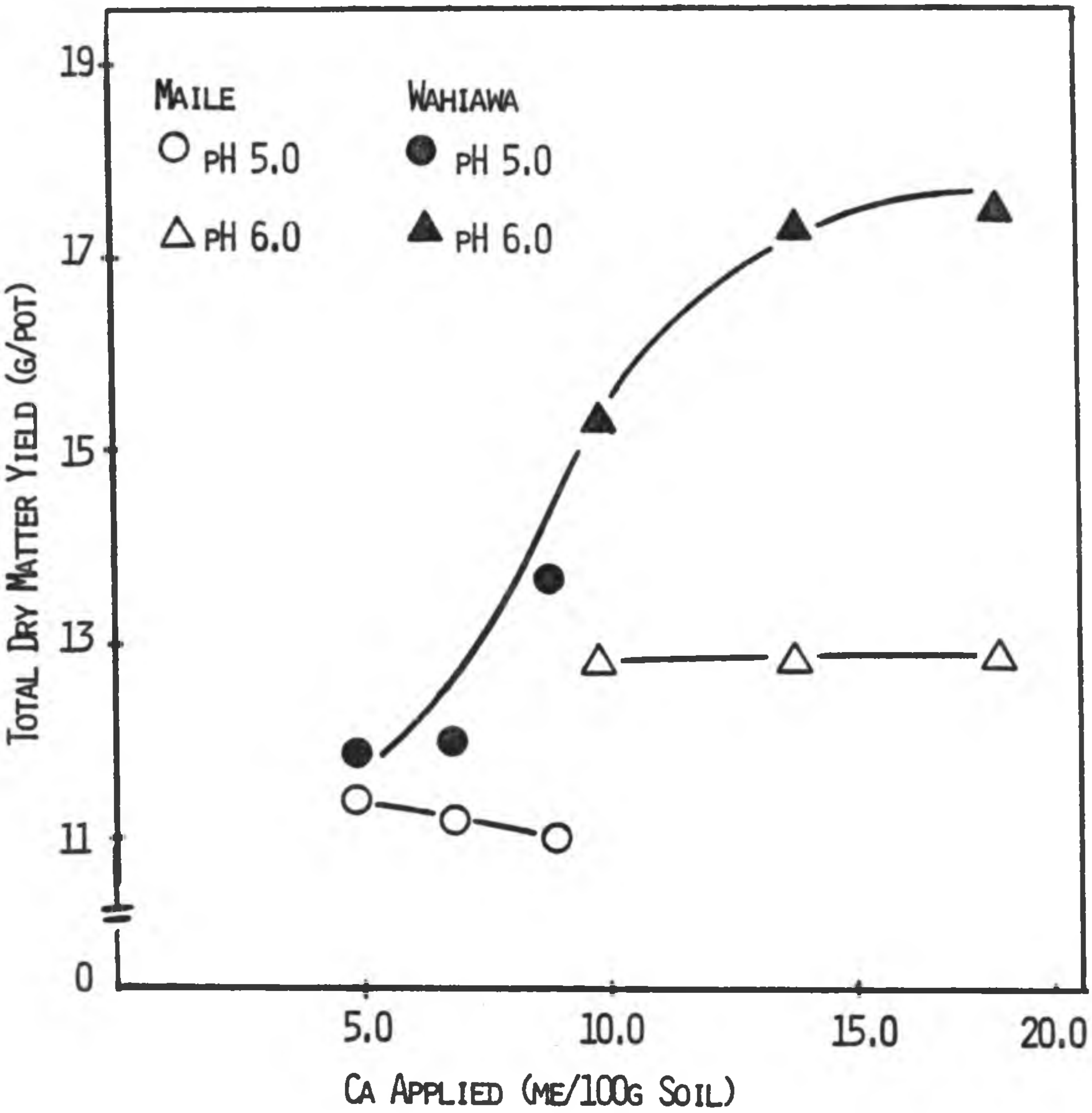

Fig. 24. Effect of applied Ca on total dry matter yield of kikuyugrass.

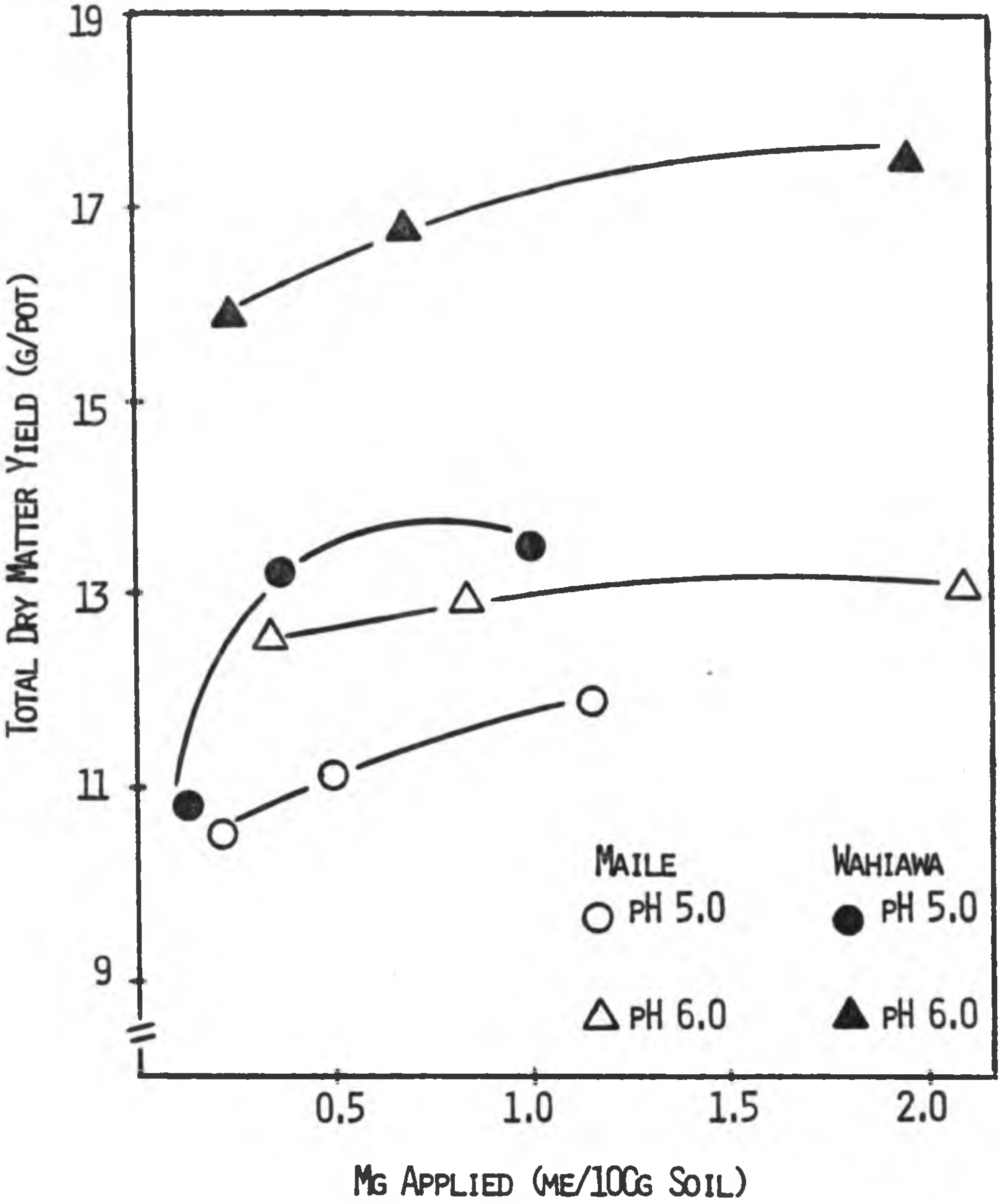

Fig. 25. Effect of applied Mg on total dry matter yield of kikuyugrass.

Mg at pH 5.0; however, at pH 6.0, dry matter production also increased but not significantly. Dry matter yield increased with increasing applied Mg at both pH levels in Wahiawa (B) soil. Total dry matter yield at pH 6.0 was greater than that at pH 5.0 in both soils. Tamimi et al (1967) reported that a significant increase in the yield of kikuyugrass on the Island of Hawaii, resulted from the application of magnesium sulfate. In a solution culture experiment, Cassidy (1972) also showed a significant yield response in kikuyugrass to Mg and S when applied in combination but not when applied separately.

Significant Mg x Ca interaction on the total dry matter yield was found in Maile soil at pH 5.0 only (Fig. 26). At low and medium Ca levels, the dry matter yield increased with increasing applied Mg; however, at high Ca level, there was no significant increase in yield with increasing Mg. Also, the rate of increase of dry matter yield as a result of increasing applied Mg, decreased with increasing applied Ca. This situation may be due to the optimum yield of kikuyugrass was achieved when the soil Ca level was low, further raising of the Ca level would therefore lower the efficiency of the dry matter yield brought about by the increasing Mg application.

There was significant Ca x Mg interaction on total dry matter yield in Wahiawa (B) soil only at pH 6.0 (Fig. 27). At low and medium Ca levels, total dry matter

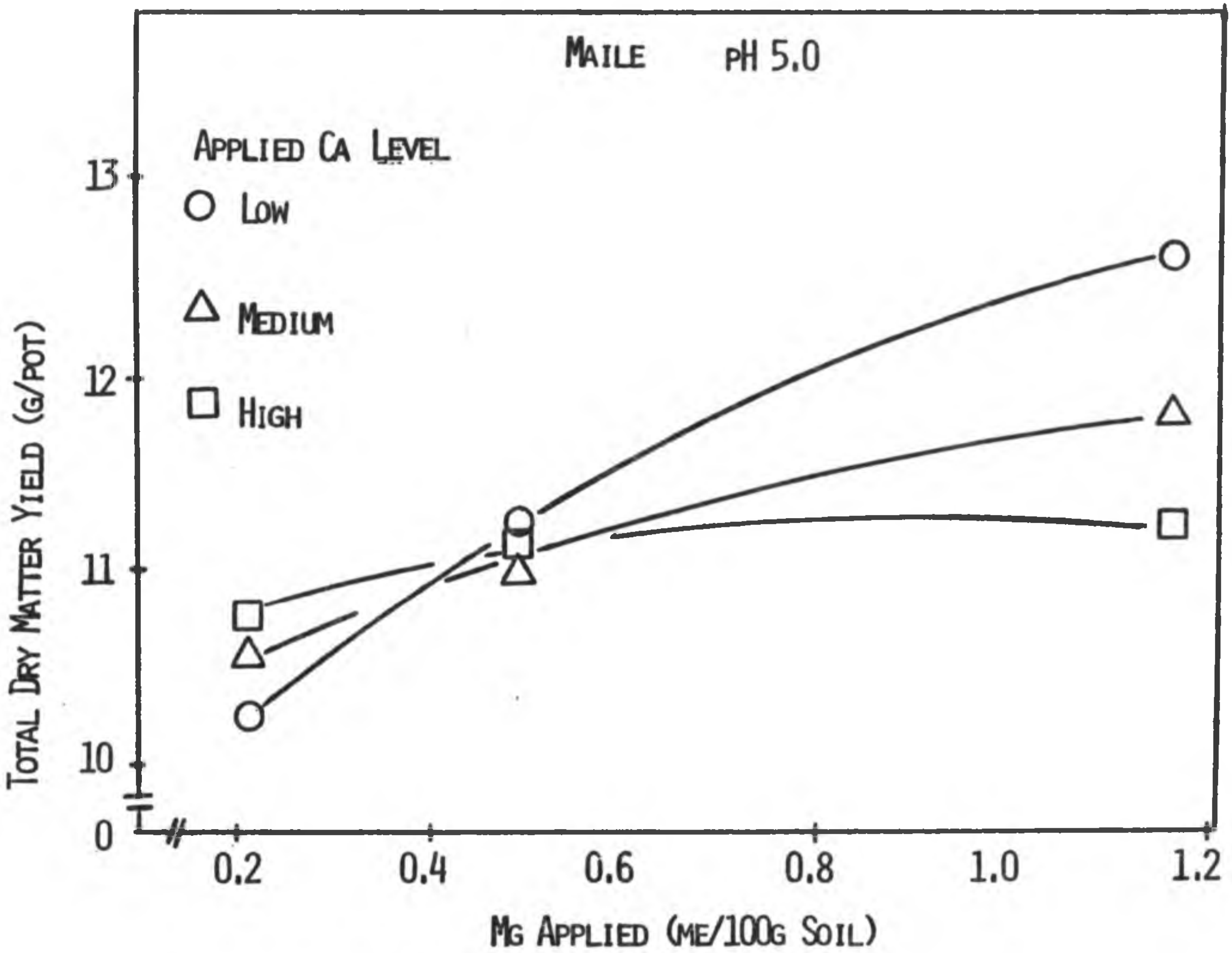

Fig. 26. Relationship between applied Mg and total dry matter yield of kikuyugrass at various levels of applied Ca in Maile soil at pH 5.0.

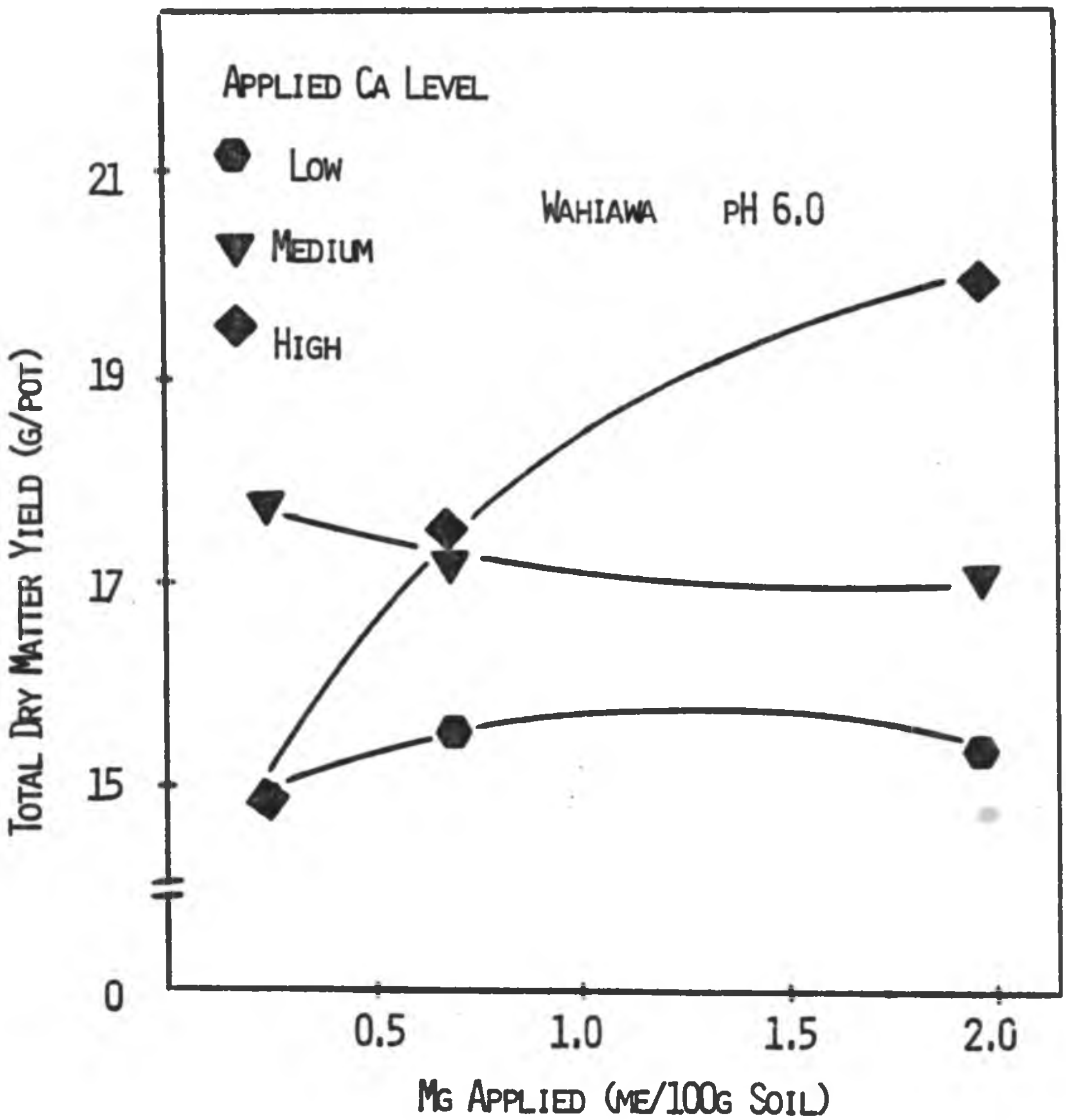

Fig. 27. Relationship between applied Mg and total dry matter yield of kikuyugrass at various levels of Ca in Wahiawa soil at pH 6.0.

yield was not affected significantly by increasing levels of Mg. However, at high levels of applied Ca, total dry matter yield increased with increasing level of soil Mg. It appears that optimium growth of kikuyugrass was approached at the high Ca treatment thus making Mg more effective in increasing the dry matter production.

Total dry matter yield was significantly higher at pH 6.0 than at 5.0 in both soils (Table 11). At a comparable pH level, Wahiawa (B) soil produced more dry matter than Maile soil (Table 11).

The effect of applied K, Ca and Mg fertilizers and their combinations on concentration and uptake of K by kikuyugrass

Increasing application rate of K increased tissue K concentration in kikuyugrass grown in both soils and at both pHs (Fig. 28). Tissue K concentration was not affected by soil pH in both soils. Kikuyugrass grown in Wahiawa soil consistently had higher tissue K than that in Maile soil which may be due to the fact that four times as much soil per pot was used for the Wahiawa (B) than the Maile soil (2000g vs. 500g). Due to a great difference in their bulk densities, a greater amount of K (quantitative basis) was available for plant grown in Wahiawa (B) than in Maile soils. Tissue K in kikuyugrass grown in both soils at pH 5.0 and 6.0 was a function of soil K level.

Table 11. Effect of soil pH on dry matter yield, mineral composition and grass tetany ratio of Kikuyugrass grown in Maile and Wahiawa (B) soils.

pH	Yield (g/pot)	Mineral concentration (%) P	K	Ca	Mg	Total uptake (mg/pot) P	K	Ca	Mg	Grass Tetany Ratio
					------Maile-----					
5.0	11.2b +/	0.15a	1.90b	0.39a	0.44a	16.2b	224.2b	41.8a	48.1a	1.14b
6.0	12.8a	0.13b	2.50a	0.34b	0.38b	17.1a	328.4a	42.7a	47.0a	1.68a
	**	**	**	**	**	**	**	ns	ns	**
					-----Wahiawa (A)-----					
5.0	12.5b +/	0.26a	3.35b	0.47b	0.60a	31.0b	441.7b	57.3b	73.5b	1.37b
6.0	16.7a	0.24b	4.00a	0.53a	0.59a	39.1a	691.6a	86.5a	95.3a	1.74a
	**	**	**	**	ns	**	**	**	**	**

+/ Means in the same column followed by the same letter are not significantly different at 5% level determined by Duncan Multiple Range Test.

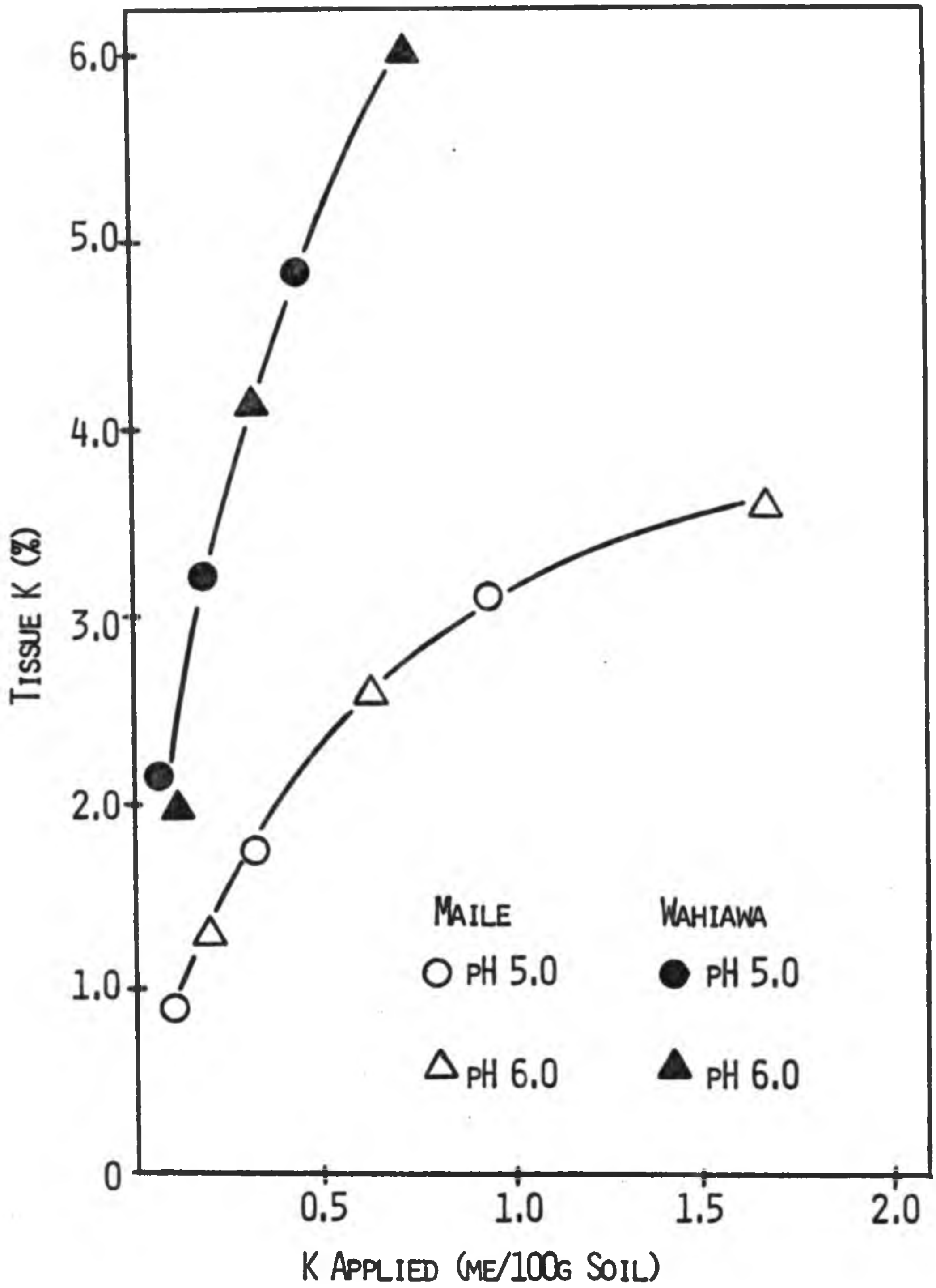

Fig. 28. Effect of applied K on tissue K concentration of kikuyugrass.

Total K uptake by kikuyugrass increased with increasing soil K in both Maile and Wahiawa (B) soils (Fig. 29). A maximium total uptake of about 500 mg K/pot for the four harvests which lasted for about eight months was obtained in the Maile soil. Maximium total K uptake value was not achieved in the Wahiawa (B) soil under conditions of this experiment. Total K uptake by kikuyugrass as affected by soil K was independent of soil pH levels in both soils (Fig. 29).

Tissue K level in kikuyugrass was not influenced by soil levels of Ca or Mg (Tables 12 and 13, respectively) in both soils and at two pH levels. Tamimi et al (1976) also showed the lack of influence of Ca and Mg in soil on K uptake by kikuyugrass. Ohno and Grunes (1985) reported that K concentrations of shoot and root of winter wheat, as well as the K influx rate were not affected by the Mg concentration in nutrient solution. However, Smith (1981) reported that there was a decrease in K concentration of kikuyugrass grown in a sand medium when Mg concentration in the nutrient solution was increased. Total K uptake by kikuyugrass was not affected significantly by the application of various amounts of Ca to both soils except that in the Wahiawa (B) soil at pH 6.0, where the application of Ca increased total K uptake (Table 14). Total K uptake by kikuyugrass was not significantly affected by applied Mg, except in the

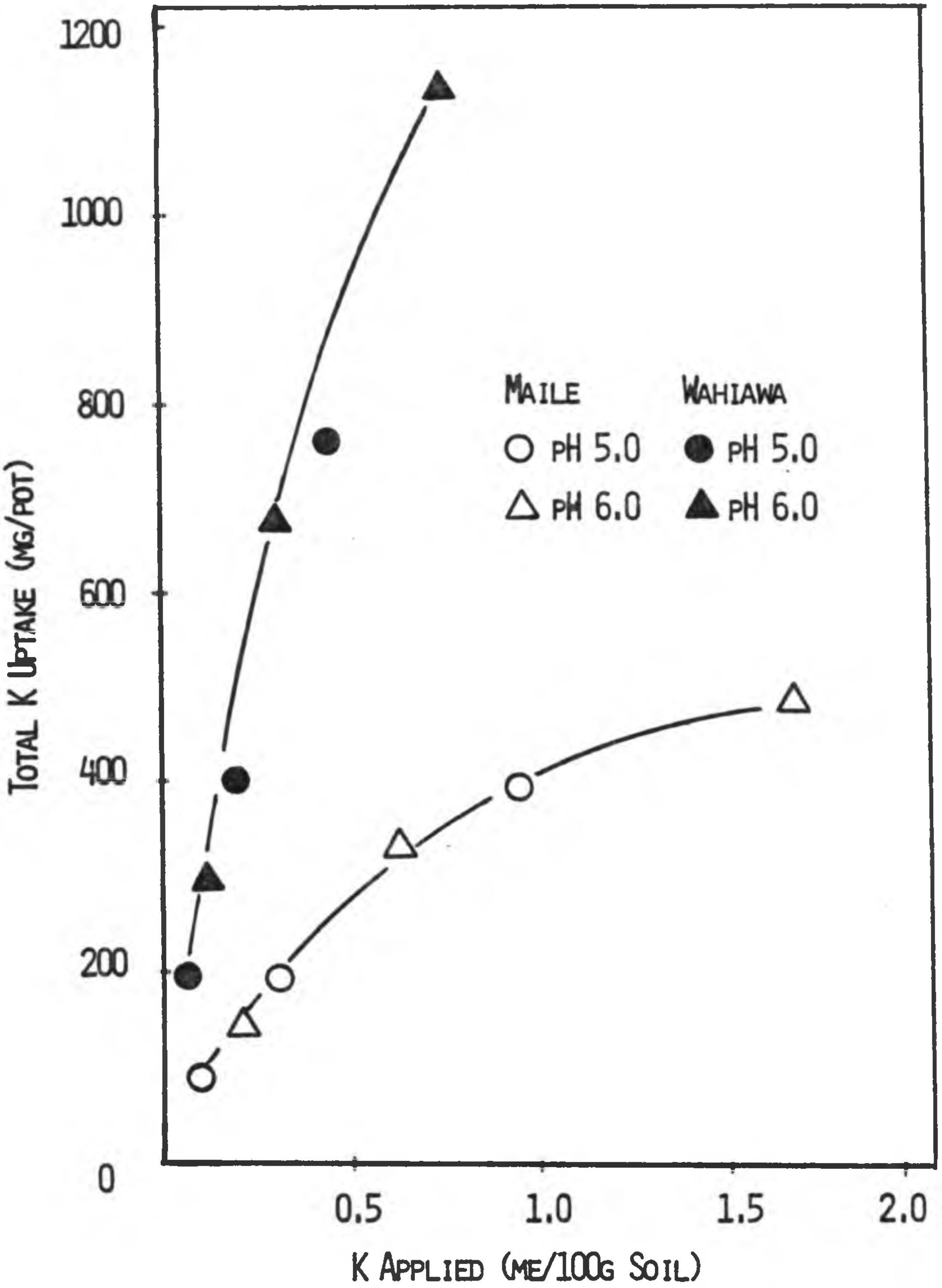

Fig. 29. Effect of applied K on total K uptake by kikuyugrass.

Table 12. Effect of applied Ca on K concentration of kikuyugrass grown in Maile and Wahiawa (B) soils at pH 5.0 and pH 6.0

Level of Ca Applied	K concentration (%) pH 5.0 Maile	pH 5.0 Wahiawa (B)	pH 6.0 Maile	pH 6.0 Wahiawa (B)
Low	1.89a +/	3.40a	2.45a	4.03a
Medium	1.90a	3.32a	2.48a	3.95a
High	1.92a	3.20a	2.50a	4.01a
	ns	ns	ns	ns

+/ Means in the same column followed by the same letter are not significantly different at 5% level determined by Duncan Multiple Range Test.

Table 13. Effect of applied Mg on K concentration of kikuyugrass grown in Maile and Wahiawa (B) soils at pH 5.0 and pH 6.0.

Level of Mg Applied	K concentration (%) pH 5.0 Maile	pH 5.0 Wahiawa (B)	pH 6.0 Maile	pH 6.0 Wahiawa (B)
Low	1.97a+/	3.38a	2.53a	3.97a
Medium	1.91a	3.29a	2.47a	4.01a
High	1.89a	3.38a	2.50a	4.01a
	ns	ns	ns	ns

+/ Means in the same column followed by the same letter are not significantly different at 5% level determined by Duncan Multiple Range Test.

Table 14. Effect of applied Ca on total K uptake by kikuyugrass grown in Maile and Wahiawa (B) soils at pH 5.0 and pH 6.0.

Level of Ca Applied	Total K Uptake (mg/pot) pH 5.0 Maile	pH 5.0 Wahiawa (B)	pH 6.0 Maile	pH 6.0 Wahiawa (B)
Low	224.6a +/	418.6a	322.1a	644.1b
Medium	224.1a	442.5a	322.6a	709.6a
High	223.8a	464.1a	340.4a	721.0a
	ns	ns	ns	**

+/ Means in the same column followed by the same letter are not significantly different at 5% level determined by Duncan Multiple Range Test.

Wahiawa (B) soil at pH 6.0, where there was an increase in the total uptake of K by this grass associated with increasing application of Mg to the soil (Table 15).

Significant interaction between applied Ca and Mg on the K concentration of kikuyugrass was found in Wahiawa (B) soil at pH 6.0 (Table 16). At low and medium levels of soil Ca, tissue K concentration increased with increasing applied Mg, while at high level of soil Ca, tissue K decreased significantly with increasing Mg application.

At both pH levels, K concentration and total K uptake were higher in Wahiawa (B) than in Maile soil (Table 11). On the other hand, significantly greater K concentration and total K uptake were found at pH 6.0 than at pH 5.0 in both soils (Table 11).

The effect of applied K, Ca and Mg fertilizers and their combinations on concentration and uptake of Ca by kikuyugrass

Increasing application of K rate drastically lowered tissue Ca concentration in kikuyugrass grown in both Maile and Wahiawa (B) soils (Fig. 30); such a response, at the same time was not affected significantly by soil pH. Tamimi et al (1976) also reported a similar trend in a greenhouse study of the effect of soil K, Ca and Mg on the nutritional status of kikuyugrass and pangolagrass. Smith (1981), in a sand culture study on the effect of K:Na and K:Mg ratio on ionic levels in various tropical grasses,

Table 15. Effect of applied Mg on total K uptake by kikuyugrass grown in Maile and Wahiawa (B) soils at pH 5.0 and pH 6.0.

Level of Mg Applied	Total K Uptake (mg/pot) pH 5.0 Maile	pH 5.0 Wahiawa (B)	pH 6.0 Maile	pH 6.0 Wahiawa (B)
Low	221.1a+/	379.1a	324.5b	660.8b
Medium	221.5a	464.4a	325.3b	680.3b
High	229.9a	481.6a	335.3a	733.5a
	ns	ns	ns	**

+/ Means in the same column followed by the same letter are not significantly different at 5% level determined by Duncan Multiple Range Test.

Table 16. Effect of applied Mg on K concentration of kikuyugrass grown in various levels of soil Ca in Wahiawa (B) soil at pH 6.0.

Level of Applied Mg	Ca	Tissue K (%)
		+/
Low	Low	3.89c
Medium	Low	4.02b
High	Low	4.19a
		**
Low	Medium	3.81c
Medium	Medium	3.95b
High	Medium	4.09a
		**
Low	High	4.19a
Medium	High	4.09b
High	High	3.75c
		**

+/ Means in the same column followed by the same letter are not significantly different at 5% level determined by Duncan Multiple Range Test.

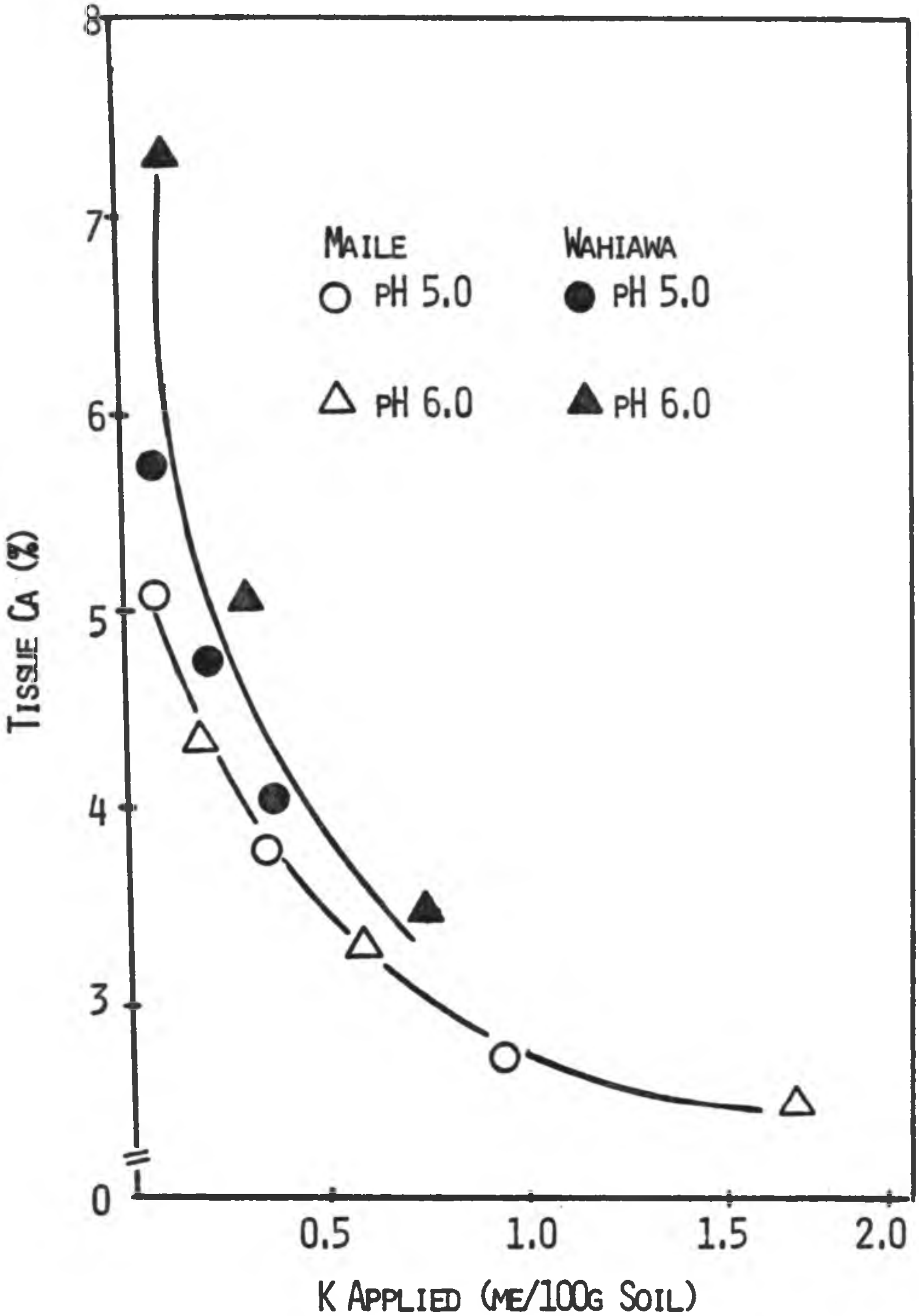

Fig. 30. Effect of applied K on tissue Ca concentration of kikuyugrass.

reported that tissue Ca of kikuyugrass was not significantly affected by K contents in the nutrient solution.

The variation in total Ca uptake as affected by increasing applied K in both soils and pH levels is shown in Table 17. In general, the total Ca uptake by kikuyugrass decreased with increasing applied K except that in the Wahiawa (B) soil at pH 5.0, where the effect was not significant.

Tissue Ca concentration increased with increasing applied Ca in both soils at both pH levels (Fig. 31). A similar situation was observed by Tamimi et al (1976) and Azmi et al (1976). However, higher tissue Ca concentration was observed at pH 5.0 than at 6.0 in both soils although soil Ca at pH 6.0 was much greater than that at pH 5.0. This will be discussed in a later section.

Total Ca uptake increased with increasing applied Ca in both soils (Fig. 32). This effect was more apparent in the Wahiawa (B) than in the Maile soil. Soil pH did not seem to influence the total Ca uptake by kikuyugrass grown in both soils.

Tissue Ca concentration decreased with increasing applied Mg in both soils at both pH levels (Fig. 33). Ohno and Grunes (1985) reported that the depression in the Ca concentration in the shoot of winter wheat by increasing Mg level in the nutrient solution was due to the decrease of Ca influx rates. Tissue Ca was higher

Table 17. Effect of applied K on total Ca uptake by kikuyugrass grown in Maile and Wahiawa (B) soils at pH 5.0 and pH 6.0.

Level of K Applied	Total Ca Uptake (mg/pot) pH 5.0 Maile	Wahiawa (B)	pH 6.0 Maile	Wahiawa (B)
Low	47.5a+/	53.7a	50.3a	109.5a
Medium	42.6b	61.1a	42.8b	83.4b
High	35.3c	57.0a	35.0c	66.5c
	**	ns	**	**

+/ Means in the same column followed by the same letter are not significantly different at 5% level determined by Duncan Multiple Range Test.

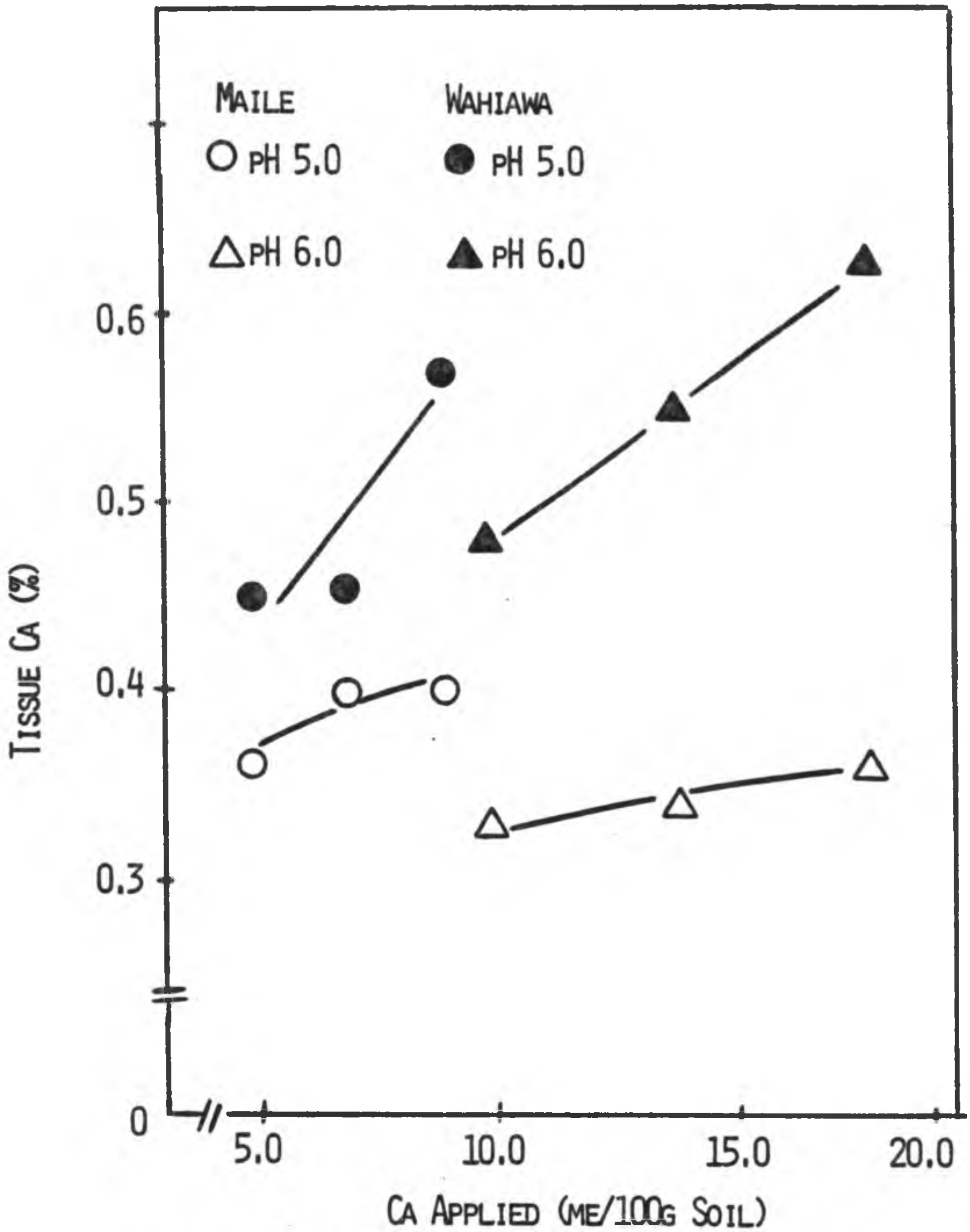

Fig. 31. Effect of applied Ca on tissue Ca concentration of kikuyugrass.

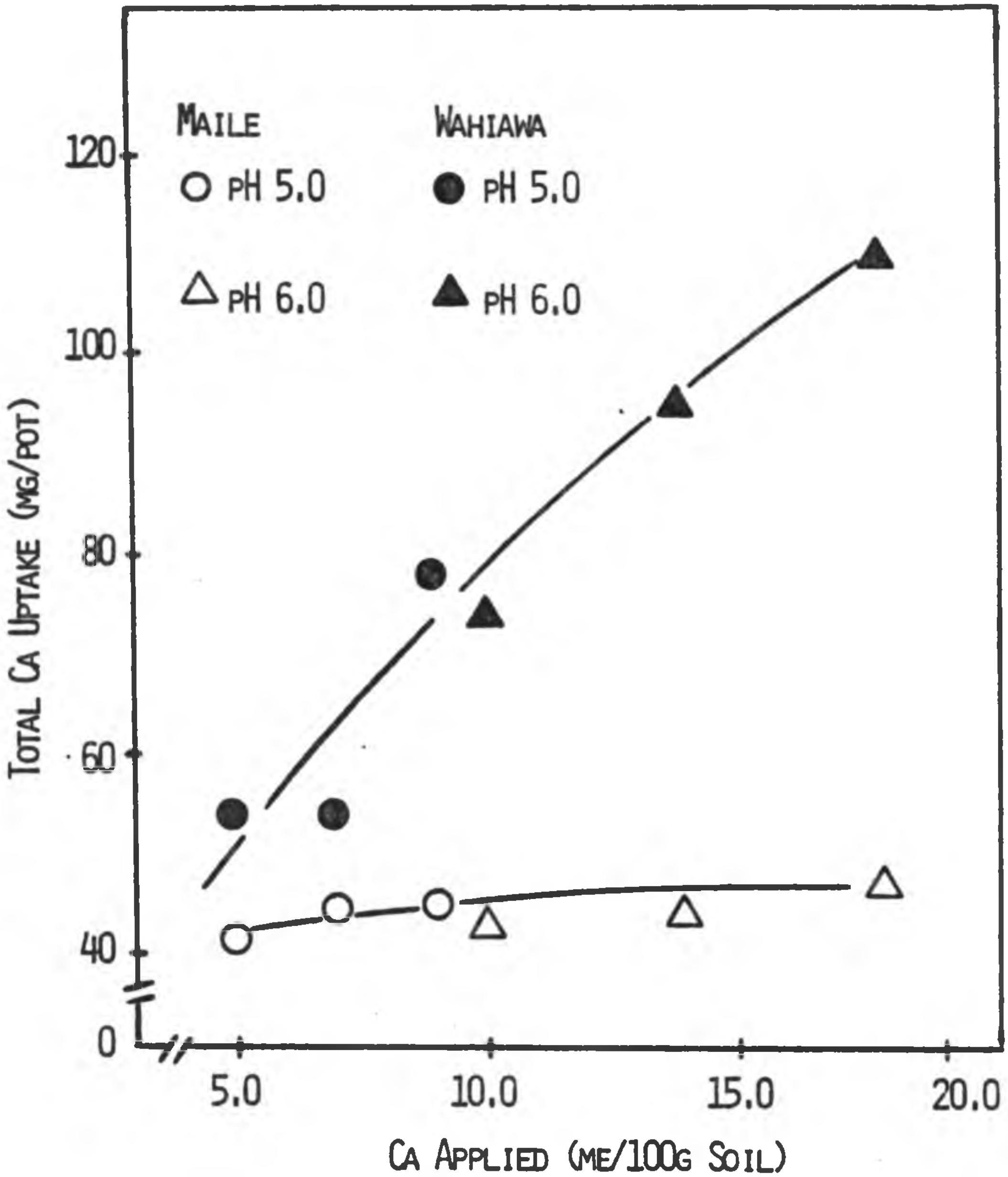

Fig. 32. Effect of applied Ca on total Ca uptake by kikuyugrass.

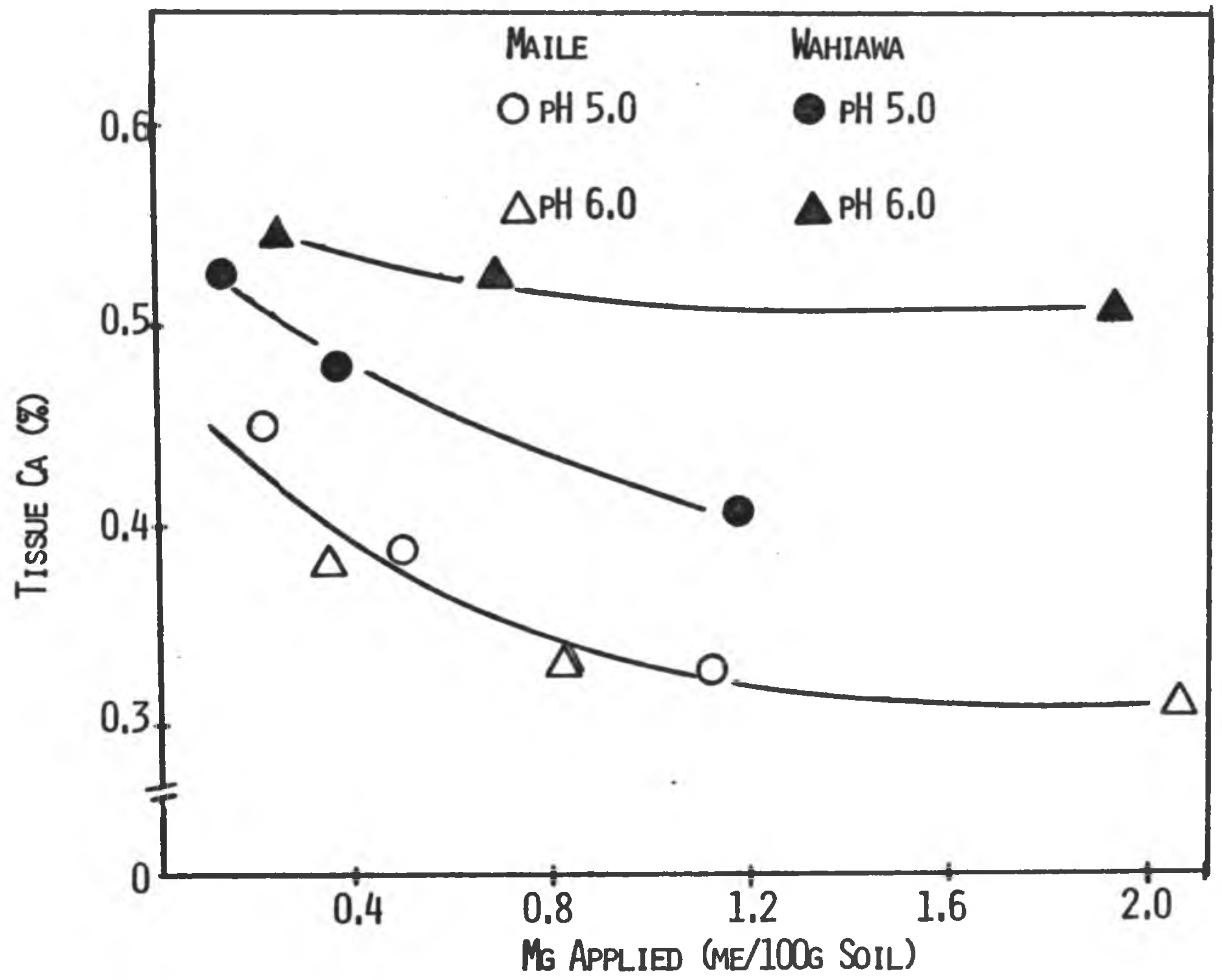

Fig. 33. Effect of applied Mg on tissue Ca concentration of kikuyugrass.

at pH 6.0 than at 5.0 in the Wahiawa soil, while in Maile soill, the response of tissue Ca of kikuyugrass to applied soil Mg levels was independent of soil pH.

The total Ca uptake by kikuyugrass grown in the Maile soil decreased with increasing applied Mg at both pH levels; however, the total Ca uptake by plants grown in the Wahiawa (B) soil was not significantly affected by soil Mg levels at both pH 5.0 and 6.0 (Table 18).

Significant interaction between applied K and Mg affecting tissue Ca concentration was observed at both pH levels in the Maile soil (Fig. 34). Tissue Ca concentration decreased by increasing applied K at both pH levels. This decrease was greater as level of applied Mg increased (Fig. 34). The higher the applied Mg level, the lower was the tissue Ca concentration at corresponding K rate.

Increasing soil K level decreased Ca concentration in kikuyugrass grown in Maile soil at pH 5.0 (Fig. 35). This decrease occurred at all soil Ca levels but tissue Ca was consistently higher at high soil Ca than those of low and medium rates.

Increasing Mg application suppressed Ca concentration of kikuyugrass grown in the Wahiawa (B) soil at pH 6.0 when soil Ca rates were low and medium but had no significant effect when soil Ca treatment was high (Fig. 36).

At both pH levels, Ca concentration and total Ca uptake were higher in Wahiawa (B) than Maile soil

Table 18. Effect of applied Mg on total Ca uptake by kikuyugrass grown in Maile and Wahiawa (B) soils at pH 5.0 and pH 6.0.

Level of Mg Applied	Total Ca Uptake (mg/pot) pH 5.0 Maile	pH 5.0 Wahiawa (B)	pH 6.0 Maile	pH 6.0 Wahiawa (B)
Low	45.2a +/	57.2a	45.8a	84.6a
Medium	42.0b	61.0a	42.2b	88.6a
High	38.0c	53.7a	40.0b	86.1a
	**	ns	**	ns

+/ Means in the same column followed by the same letter are not significantly different at 5% level determined by Duncan Multiple Range Test.

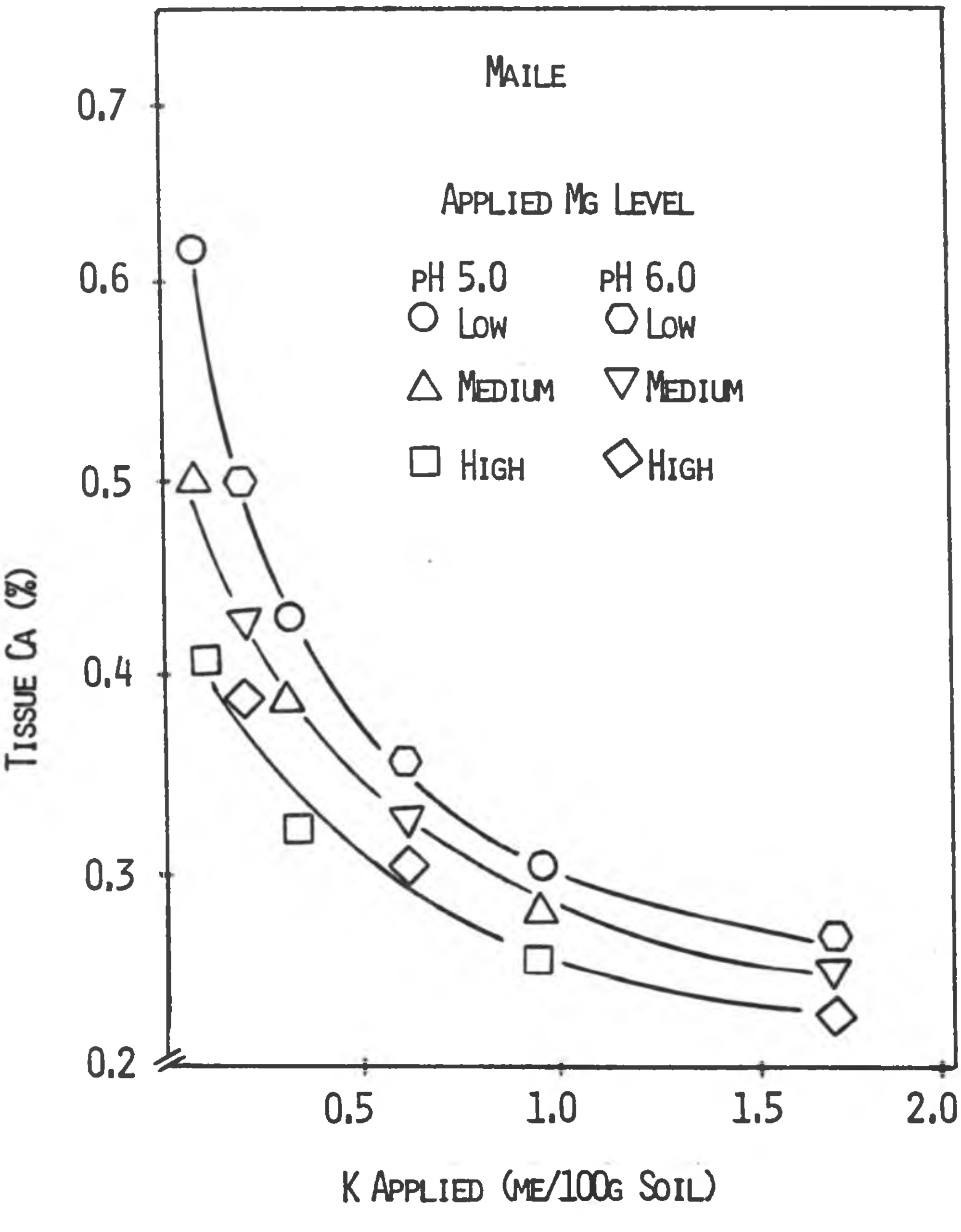

Fig. 34. Effect of applied K on tissue Ca concentration of kikuyugrass at various levels of Mg in Maile soil.

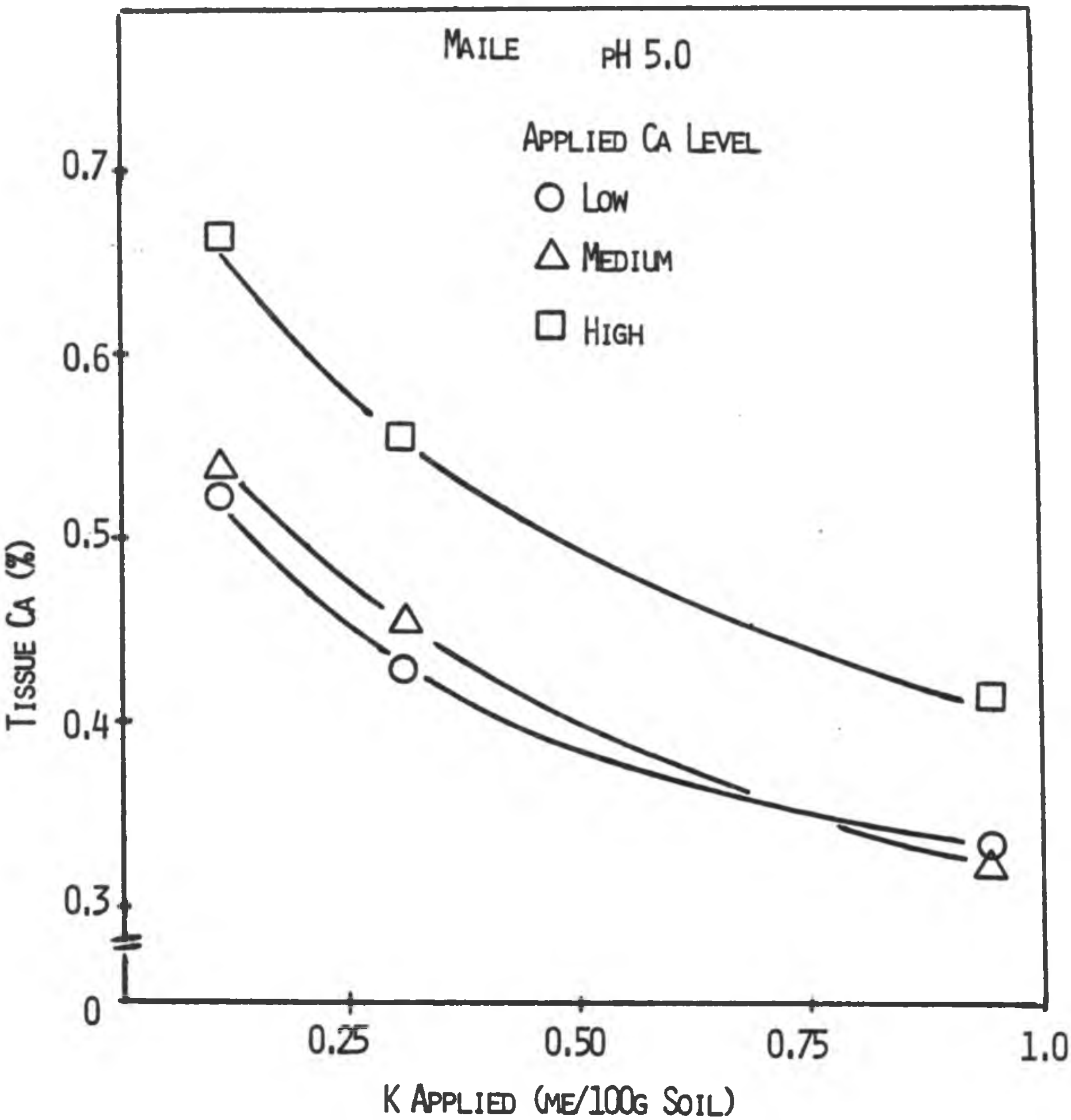

Fig. 35. Effect of applied K on tissue Ca concentration of kikuyugrass at various levels of applied Ca in Maile soil at pH 5.0.

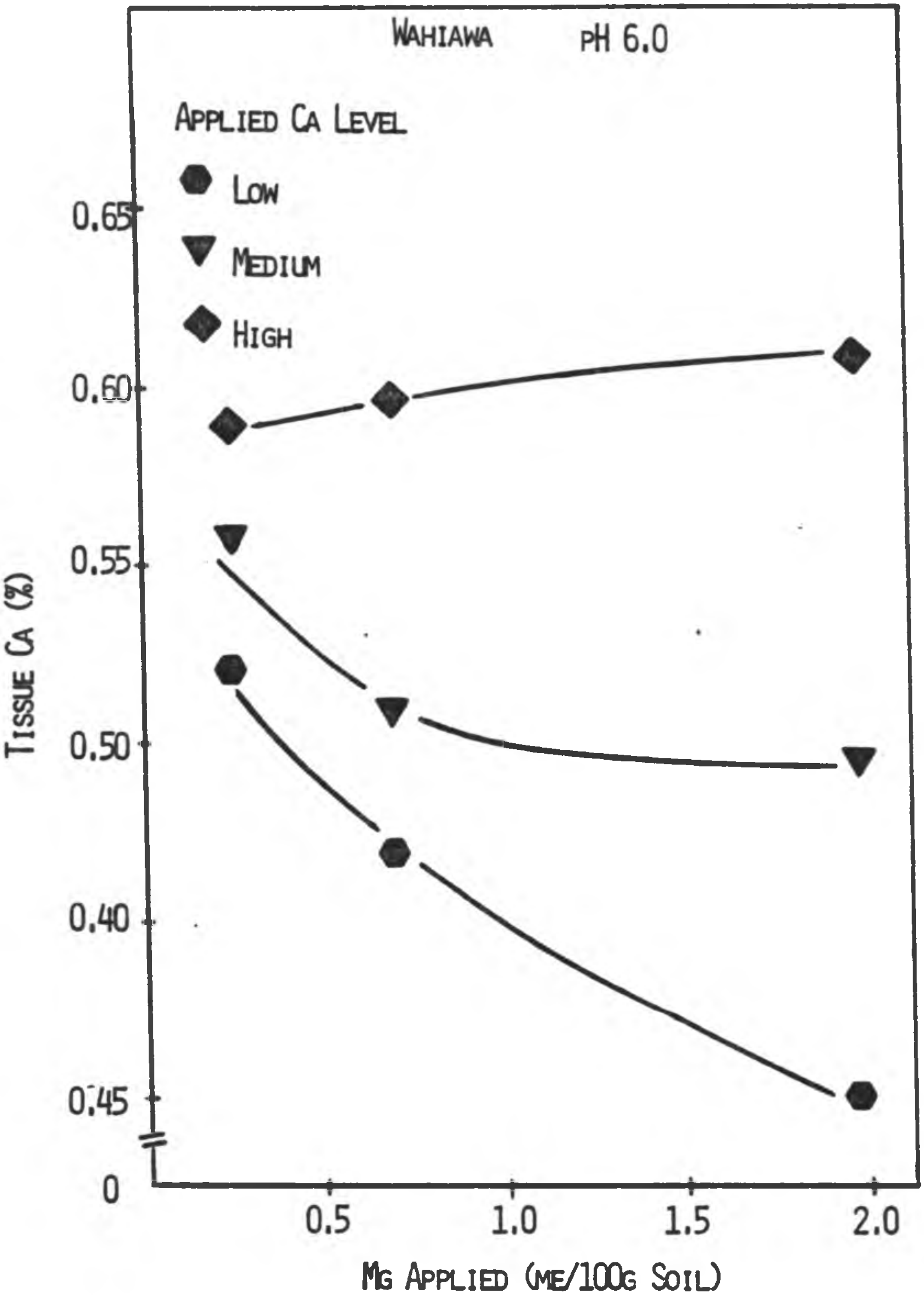

Fig. 36. Effect of applied Mg on tissue Ca concentration of kikuyugrass at various levels of applied Ca in Wahiawa (B) soil at pH 6.0.

(Table 11). In Maile soil, tissue Ca concentration was higher at pH 5.0 than at 6.0; however, a reverse trend was observed in Wahiawa (B) soil (Table 11). Total Ca uptake was not significantly different between pH 5.0 and 6.0 in Maile soil; however, it was statistically higher at the elevated soil pH in Wahiawa (B) soil (Table 11).

The effect of applied K, Ca and Mg fertilizers and their combinations on concentration and uptake of Mg by kikuyugrass

Tissue Mg concentration in plants grown in both Maile and Wahiawa (B) soils decreased with increasing soil K level (Figs. 37 and 38). A similar situation was reported by Tamimi et al (1976) and Smith et al (1981). Ohno and Grunes (1985) attributed the decrease in the Mg concentration in the shoot but not the root in winter wheat with increasing K supply in the nutrient solution to the K-Mg antagonistic mechanism in the translocation from the root to the shoot. Such translocation theory was also supported by Hannaway et al (1980). Soil pH possessed no influence on the effect of soil K level on tissue Mg concentration.

The effect of soil K on total Mg uptake by kikuyugrass is presented in Table 19. In general, the total Mg uptake was depressed by increasing soil K levels except that of Wahiawa (B) soil at pH 5.0, where the effect of soil K on the total Mg uptake was not significant.

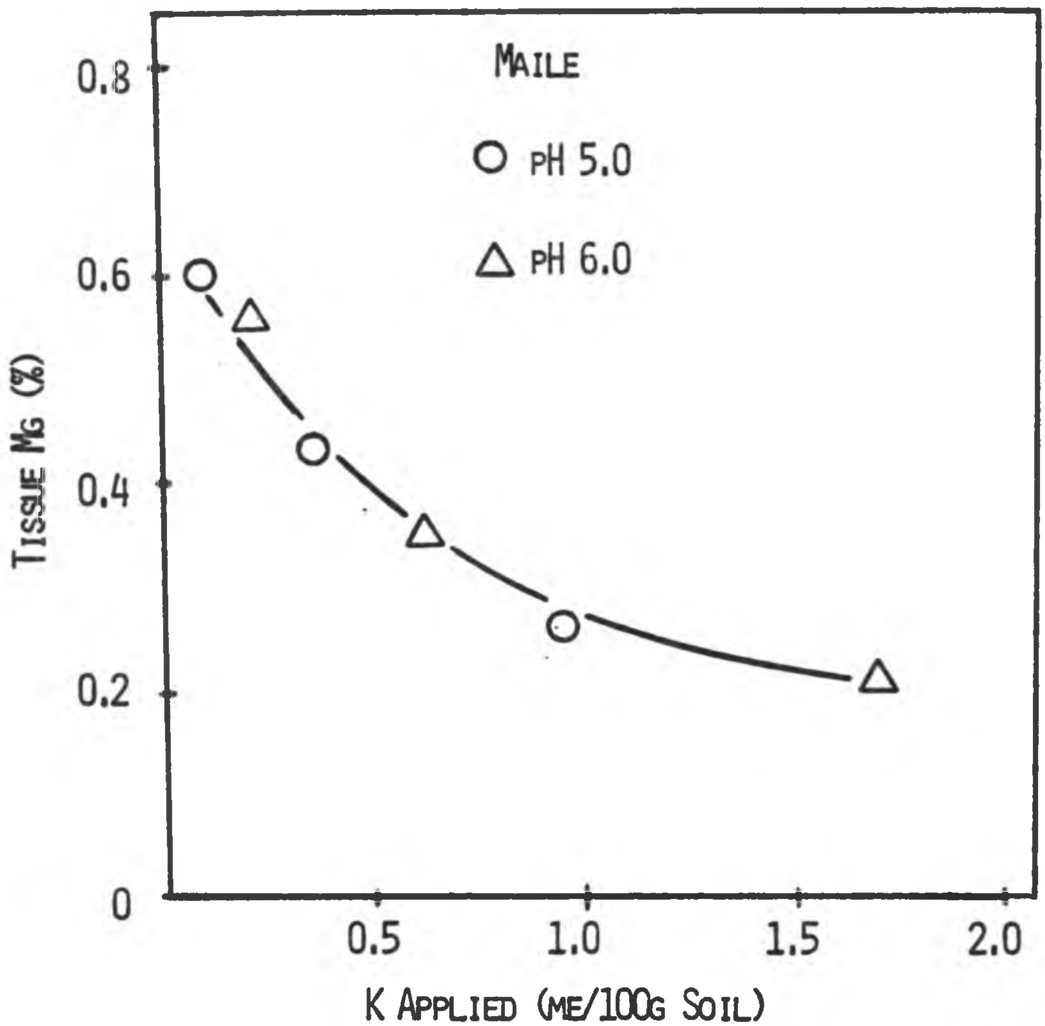

Fig. 37. Effect of applied K on tissue Mg concentration of kikuyugrass in Maile soil.

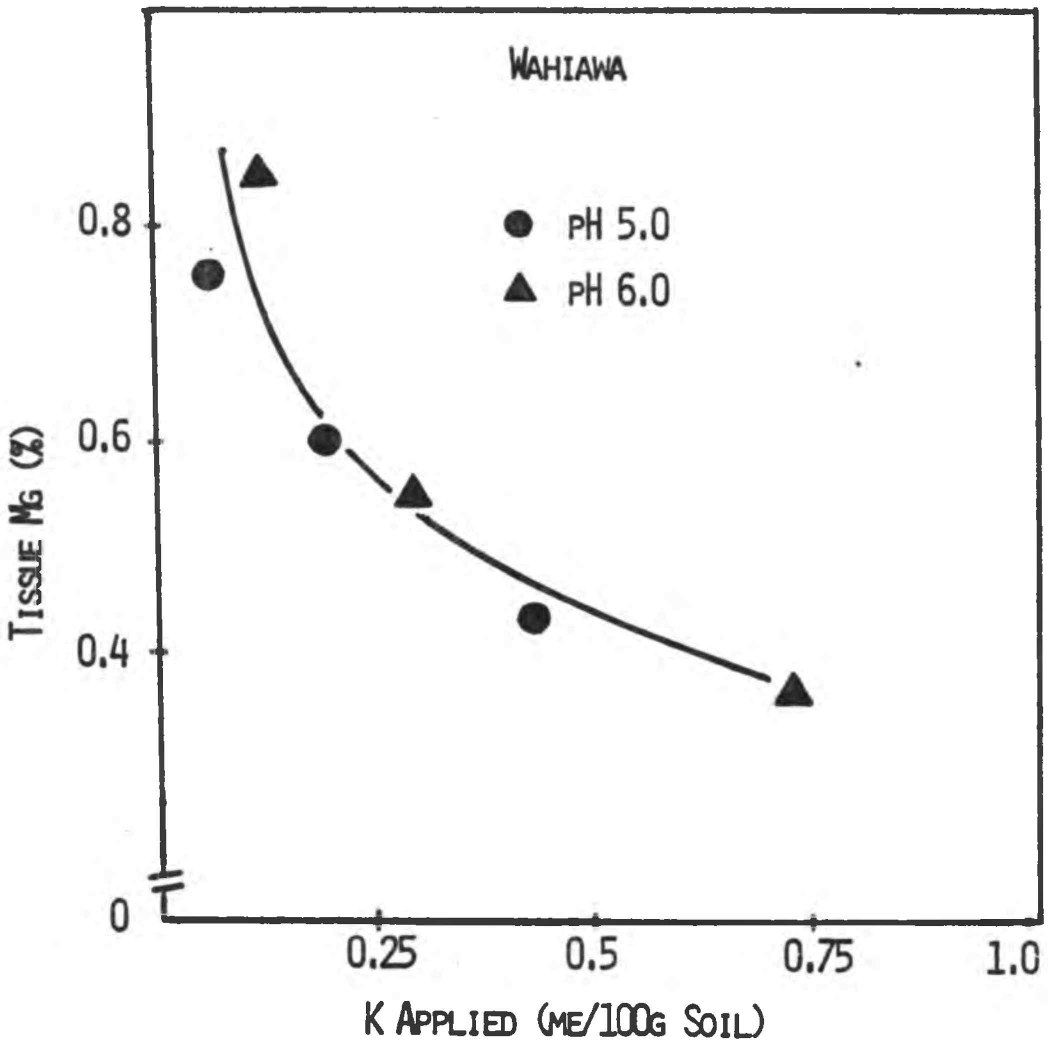

Fig. 38. Effect of applied K on tissue Mg concentration of kikuyugrass in Wahiawa (B) soil.

Table 19. Effect of applied K on total Mg uptake by kikuyugrass grown in Maile and Wahiawa (B) soils at pH 5.0 and pH 6.0.

Level of K Applied	Total Mg Uptake (mg/pot) pH 5.0 Maile	pH 5.0 Wahiawa (B)	pH 6.0 Maile	pH 6.0 Wahiawa (B)
Low	58.5a+/	72.4a	64.9a	124.4a
Medium	50.9b	78.0a	45.3b	90.9b
High	34.8c	70.1a	30.7c	70.7c
	**	ns	**	**

+/ Means in the same column followed by the same letter are not significantly different at 5% level determined by Duncan Multiple Range Test.

Magnesium concentration in kikuyugrass was not affected significantly by various levels of soil Ca in both Maile and Wahiawa (B) soils (Table 20). Similar finding was reported by Tamimi et al (1976). On the other hand, Cassidy (1972) demonstrated in a solution culture study that Mg concentration in kikuyugrass was increased by the application of Ca.

Total Mg uptake by kikuyugrass grown in Maile soil at pH 5.0 decreased where soil Ca level was high, but was not significantly affected at medium and low Ca soil levels (Table 21).

Magnesium concentration in kikuyugrass increased with increasing soil Mg levels in both Maile and Wahiawa (B) soils (Fig. 39). Similar result was obtained by Tamimi et al (1976) and Smith (1981). However, tissue Mg concentration was higher at pH 5.0 than at pH 6.0 in both soils even though both soils contained a higher concentration of Mg at pH 6.0 than at pH 5.0.

The total Mg uptake by kikuyugrass increased with increasing soil Mg level in both Maile and Wahiawa (B) soils at both pH levels (Fig. 40). In Maile soil, total Mg uptake by kikuyugrass was greater at pH 5.0 than at 6.0 at comparable application rates of Mg; however, in Wahiawa (B) soil, a reverse trend where kikuyugrass had higher total Mg uptake at pH 6.0 than at 5.0 was observed.

Table 20. Effect of applied Ca on Mg concentration of kikuyugrass grown in Maile and Wahiawa (B) soils at pH 5.0 and pH 6.0.

Level of Ca Applied	Mg concentration (%) pH 5.0 Maile	Wahiawa (B)	pH 6.0 Maile	Wahiawa (B)
Low	0.43a+/	0.62a	0.39a	0.60a
Medium	0.46a	0.58a	0.38a	0.59a
High	0.43a	0.61a	0.37a	0.58a
	ns	ns	ns	ns

+/ Means in the same column followed by the same letter are not significantly different at 5% level determined by Duncan Multiple Range Test.

Table 21. Effect of applied Ca on total Mg uptake by kikuyugrass grown in Maile and Wahiawa (B) soils at pH 5.0 and pH 6.0.

Level of Ca Applied	Total Mg Uptake (mg/pot) pH 5.0 Maile	pH 5.0 Wahiawa (B)	pH 6.0 Maile	pH 6.0 Wahiawa (B)
Low	48.9a +/	72.0a	47.6a	89.8a
Medium	49.8a	69.0a	47.6a	99.0a
High	45.6b	79.6a	45.7a	97.3a
	*	ns	ns	ns

+/ Means in the same column followed by the same letter are not significantly different at 5% level determined by Duncan Multiple Range Test.

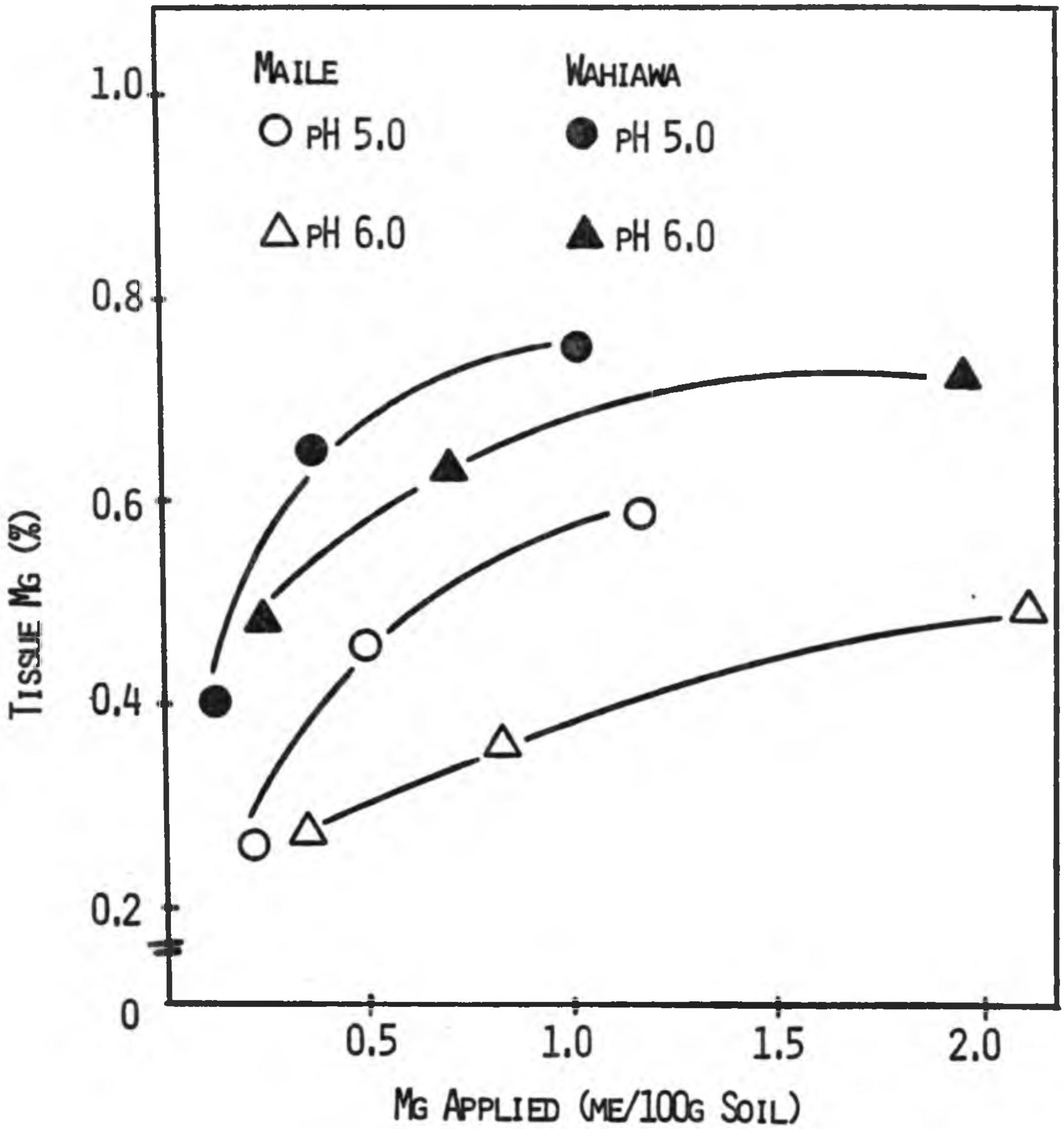

Fig. 39. Effect of applied Mg on tissue Mg concentration of kikuyugrass.

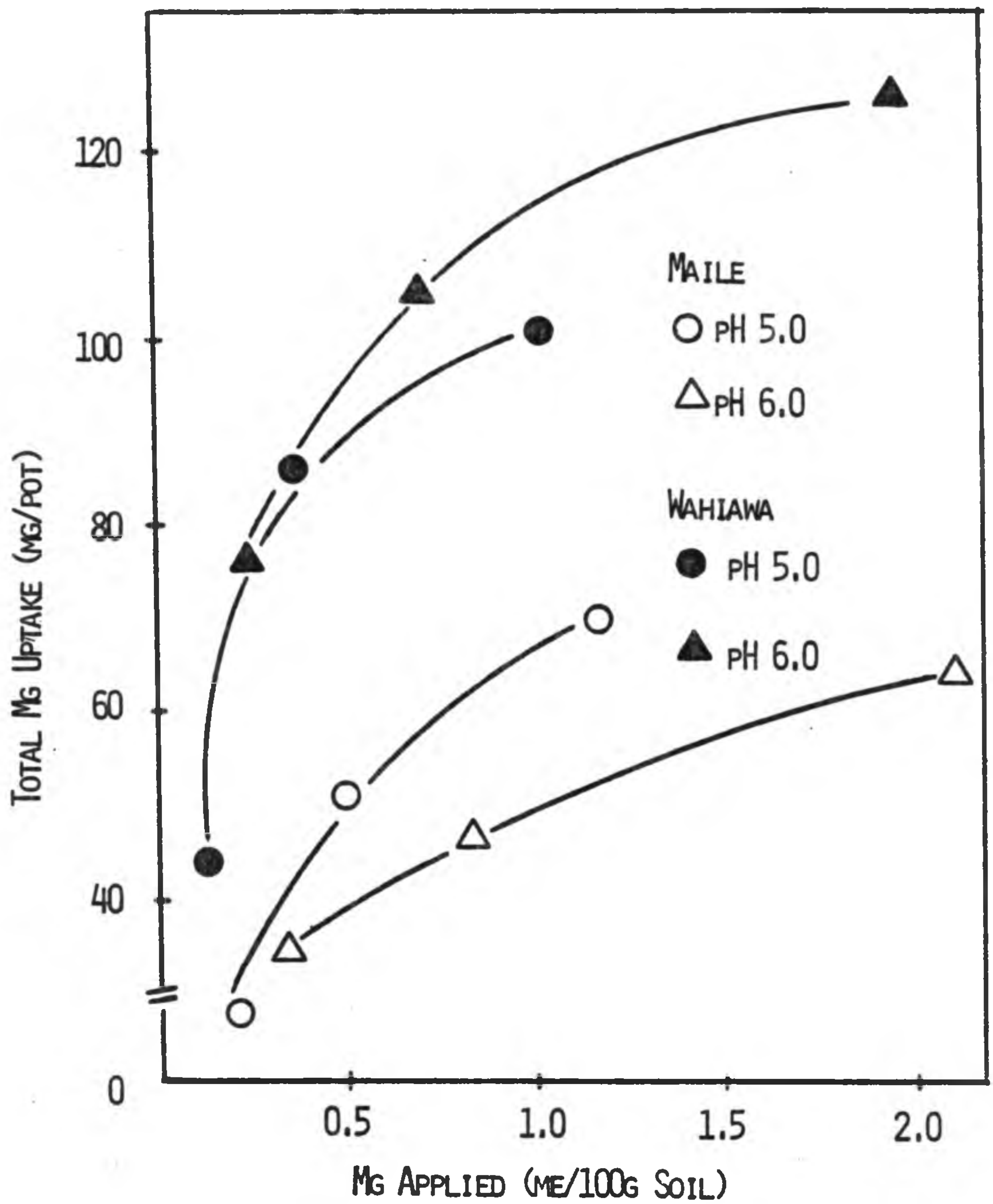

Fig. 40. Effect of applied Mg on total Mg uptake by kikuyugrass.

Tissue Ca and Mg levels in kikuyugrass grown in both soils were higher at pH 5.0 than at 6.0 despite the much lower concentrations of these two elements at pH 5.0 than at 6.0 may be due to one or more of the following reasons:

1.) The much greater dry matter production (more vigorous growth) at pH 6.0 than at 5.0 tends to produce a greater stem-leaf ratio with stem being lower in Ca and Mg concentrations than leaf. Such a situation may impose a "dilution effect" on the concentrations of these two elements in the harvested portion thus resulting in a greater concentrations of Ca and Mg in tissue of pH 5.0 than at 6.0 at comparable applied Ca and Mg levels, respectively.

2.) Both Ca and Mg might be held with higher bonding energies to the surfaces of the soils at pH 6.0 than at 5.0; therefore, their extraction by the roots of kikuyugrass may tend to be more difficult at the elevated soil pH.

3.) Both Maile and Wahiawa (B) soils contained much higher K concentration at pH 6.0 than at pH 5.0 thus causing a greater depressing effect on the tissue Ca and Mg concentration of kikuyugrass at the elevated pH level. In addition, tissue Ca was also affected in the same manner by soil Mg in both soils.

At both pH levels, tissue Mg concentration and total Mg uptake were higher in Wahiawa (B) than in Maile soil

(Table 11). In Maile soil, it was found that tissue Mg concentration was statistically higher at pH 5.0 than at 6.0 while there was no significant difference in the total Mg uptake between these two pH levels. In the case of Wahiawa (B) soil, tissue Mg concentrations at both pH 5.0 and 6.0 were not significantly different while the total Mg uptake was higher at pH 6.0 than at 5.0 (Table 11).

The effect of applied K, Ca and Mg fertilizers and their combinations on the grass tetany ratio of kikuyugrass

As described earlier, the grass tetany ratio which was used as an indicator for an imbalance among K, Ca and Mg was calculated according to the formula K/(Ca+Mg) on equivalence basis. For a given level of soil K, the grass tetany ratio was higher in Wahiawa (B) soil (Fig. 41). Hence the critical soil K value, above which the grass tetany ratio would exceed the 2.2 critical limit, was lower in Wahiawa (B) (0.4 me K/100g soil) than in Maile soil (0.85 me K/100g soil). The effect of soil K on grass tetany ratio of kikuyugrass grown in both soils was not influenced by soil pH levels.

For a given level of tissue K, the grass tetany ratio was higher in Maile than Wahiawa (B) soil, thus indicating that the corresponding (Ca+Mg) concentration in the tissue from Wahiawa (B) soil was greater than that of Maile soil (Fig.42).

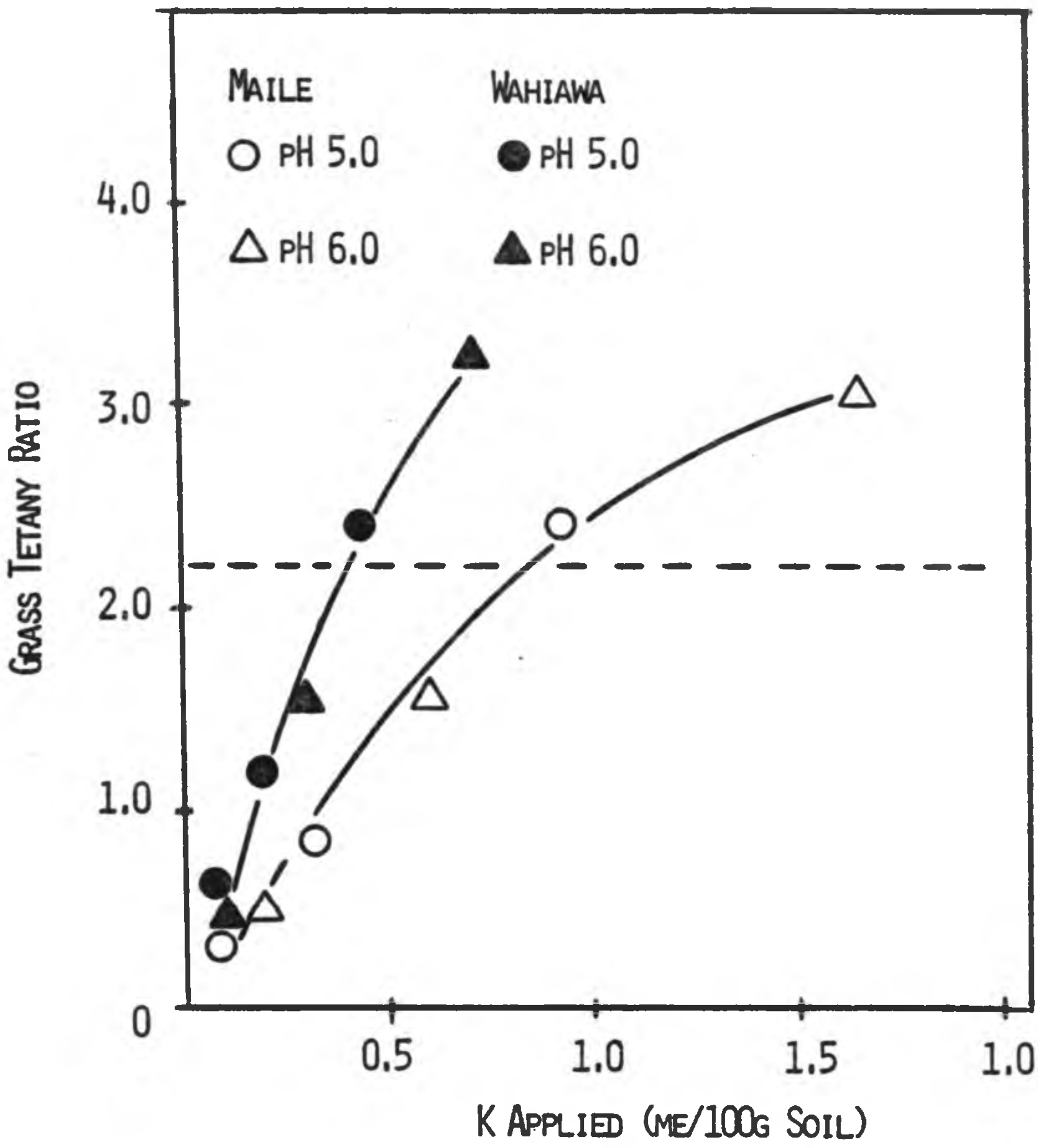

Fig. 41. Relationship between applied K and grass tetany ratio of kikuyugrass.

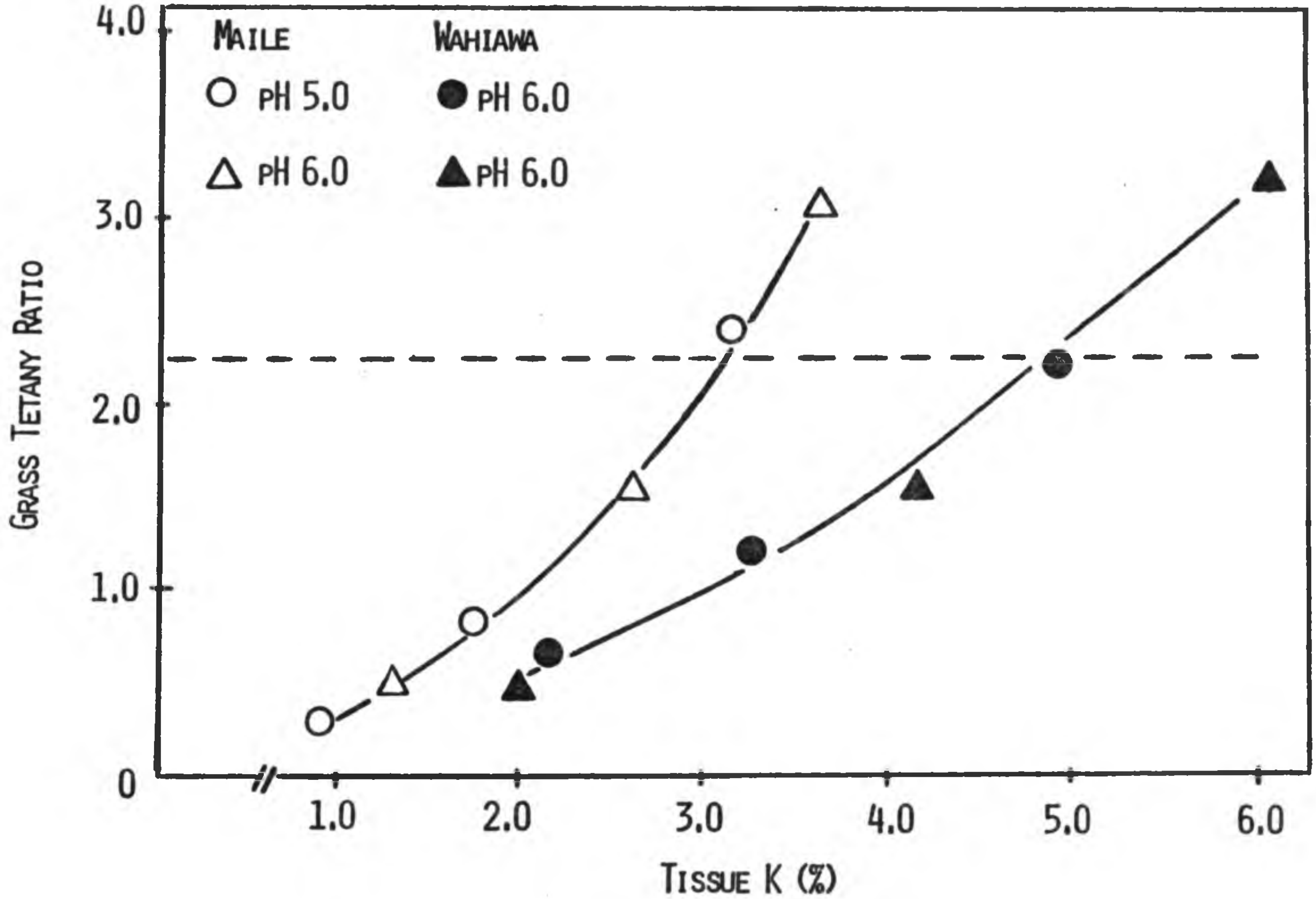

Fig. 42. Relationship between tissue K concentration and grass tetany ratio of kikuyugrass.

The relationship between the grass tetany ratio and soil Ca in both soils is shown in Table 22. The application of Ca did not affect the grass tetany ratio at both pH 5.0 and pH 6.0 in Maile soil; however, in Wahiawa (B) soil, although with no definite trend shown, the grass tetany ratio was significantly lowered at pH 5.0 where high level of Ca was applied.

Increasing levels of Mg in both soils significantly lowered grass tetany ratio at both pH levels (Fig.43). Values of the grass tetany ratio were higher at pH 6.0 than at 5.0 for both soils.

Significant interaction between applied K and Mg on the grass tetany ratio was observed in both soils and at both pH levels (Figs. 44 and 45). The grass tetany ratio decreased with increasing applied Mg at a given level of applied K. Therefore, whether the ratio would reach the critical value of 2.2 depends on both soil K and Mg.

The relationship between applied Mg and Ca, and the grass tetany ratio in Maile soil at pH 5.0 is illustrated in Fig. 46. At low Mg rate, the ratio decreased with increasing applied Ca; however, with the application of additional Mg, the trend was reversed. The significant effect of low and medium Ca levels on the grass tetany ratio diminished with increasing applied Mg, and finally, at high rate, Ca effect on the grass tetany ratio became insignificant. From this, it appears that increasing

Table 22. Effect of applied Ca on grass tetany ratio of kikuyugrass grown in Maile and Wahiawa (B) soils at pH 5.0 and pH 6.0.

Level of Ca Applied	Grass Tetany Ratio pH 5.0 Maile	Grass Tetany Ratio pH 5.0 Wahiawa (B)	Grass Tetany Ratio pH 6.0 Maile	Grass Tetany Ratio pH 6.0 Wahiawa (B)
Low	1.15a +/	1.34b	1.63a	1.79a
Medium	1.14a	1.55a	1.68a	1.72a
High	1.12a	1.21c	1.74a	1.71a
	ns	*	ns	ns

+/ Means in the same column followed by the same letter are not significantly different at 5% level determined by Duncan Multiple Range Test.

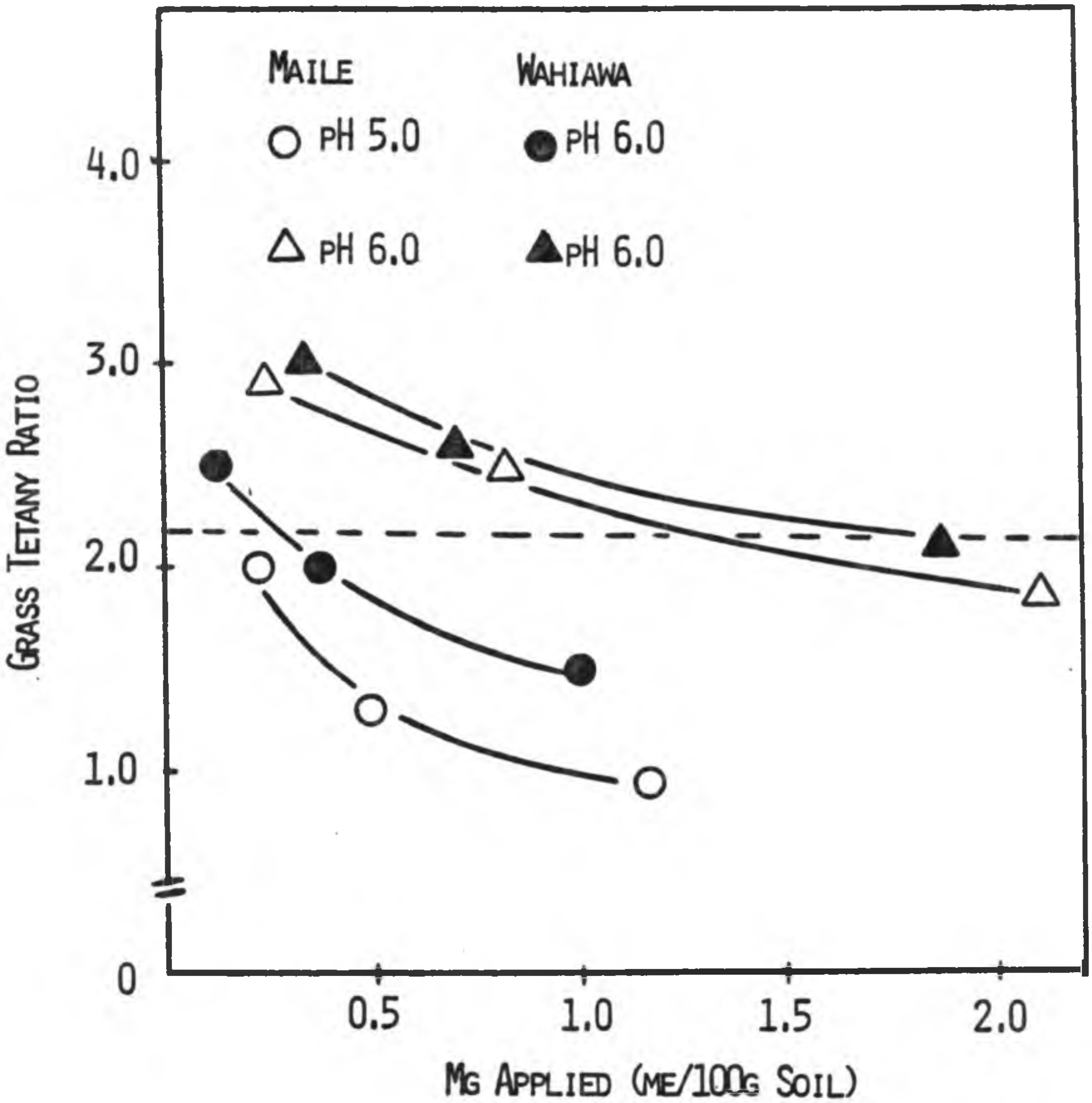

Fig. 43. Relationship between applied Mg and grass tetany ratio of kikuyugrass.

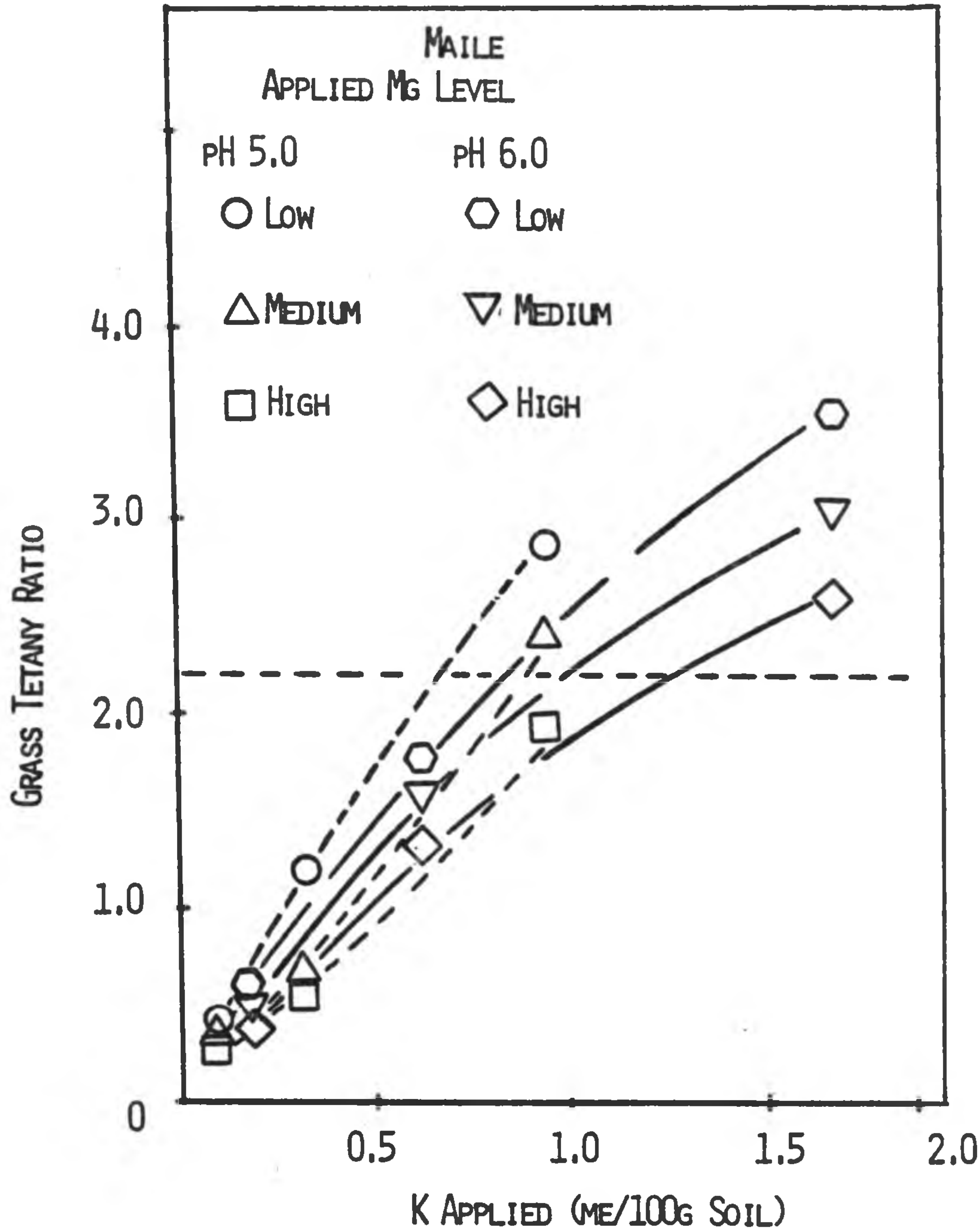

Fig. 44. Relationship between applied K and grass tetany ratio of kikuyugrass at various levels of applied Mg in Maile soil.

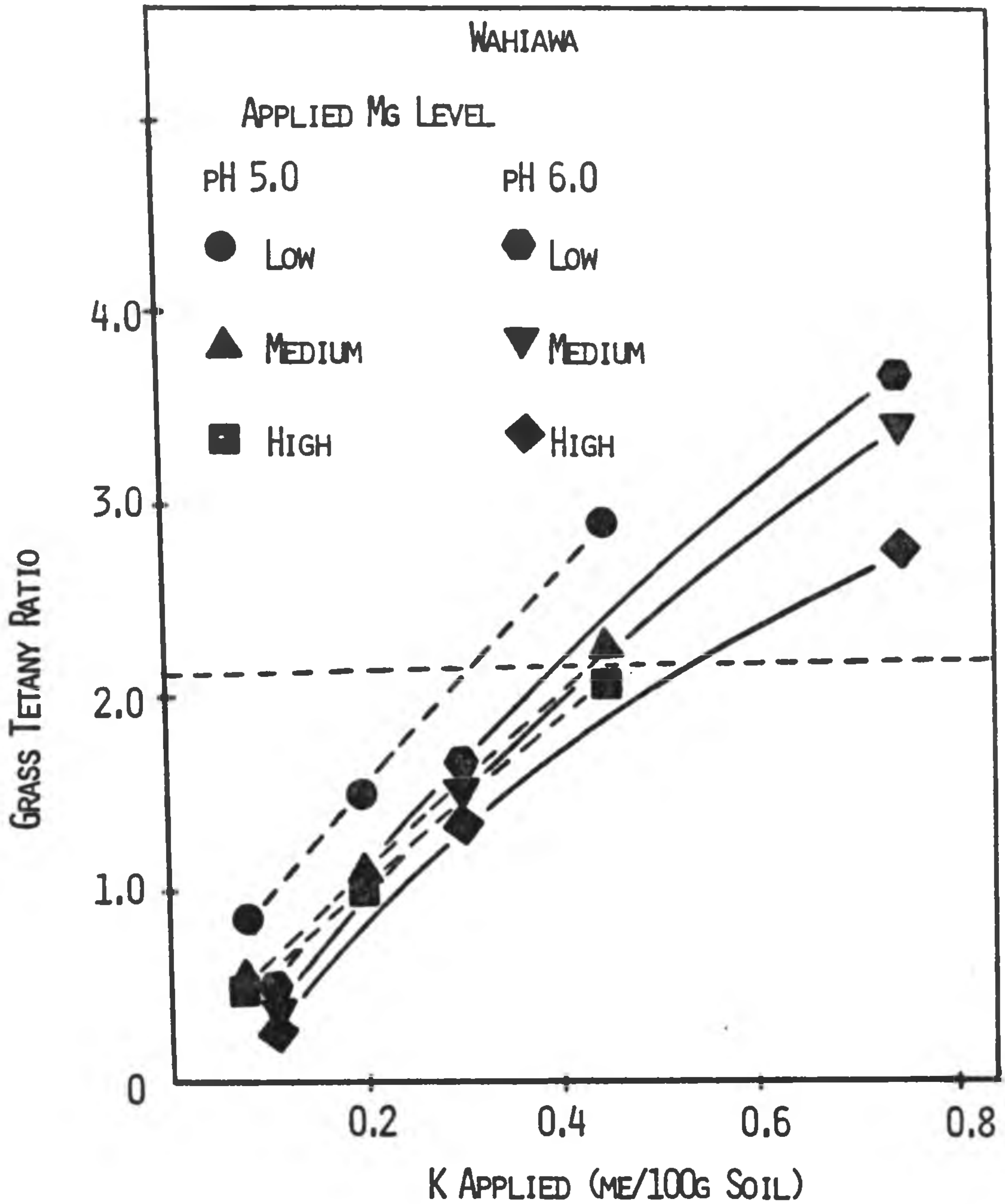

Fig. 45. Relationship between applied K and grass tetany ratio of kikuyugrass at various levels of applied Mg in Wahiawa (B) soil.

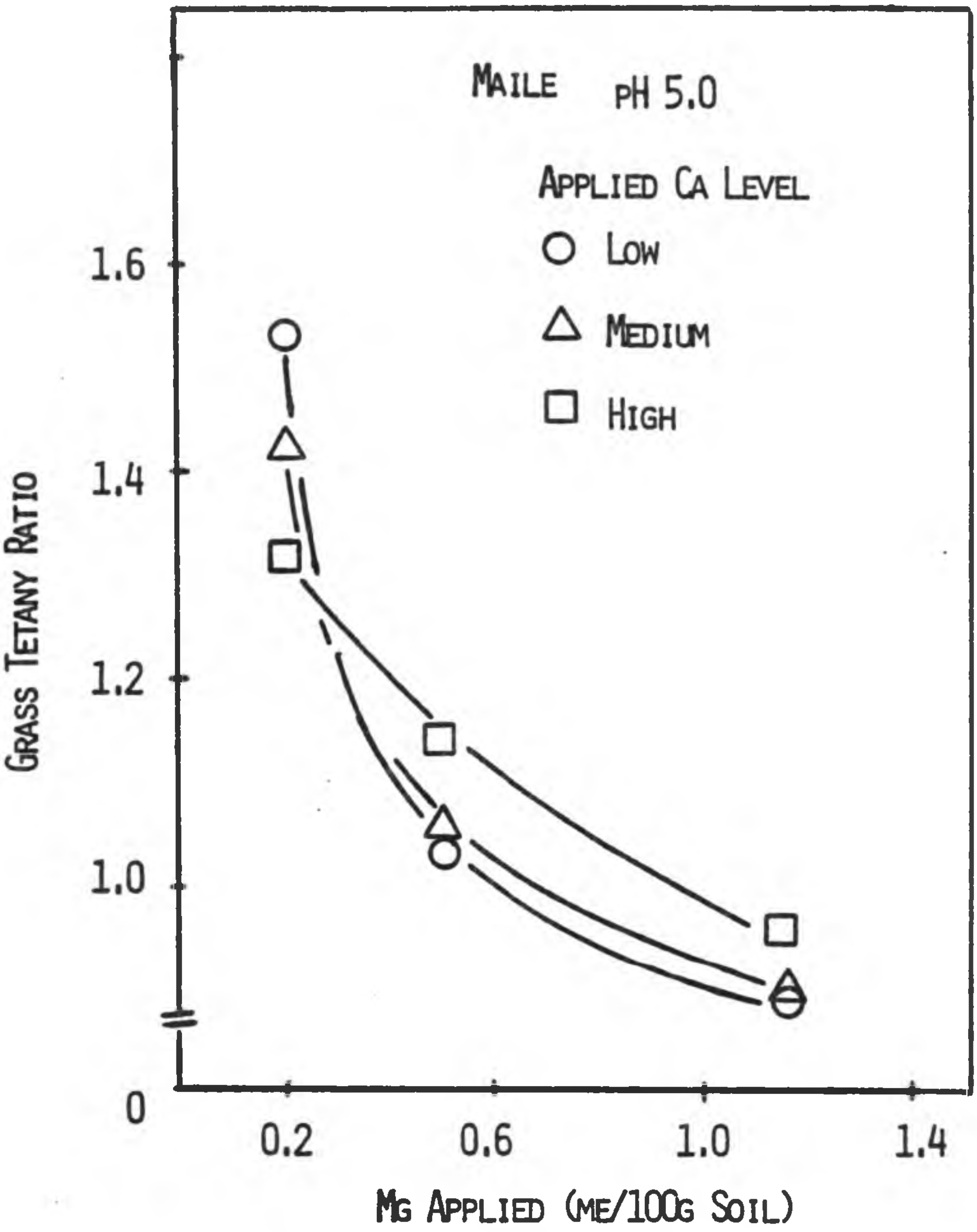

Fig. 46. Effect of applied Mg on grass tetany ratio of kikuyugrass at various levels of applied Ca in Maile soil at pH 5.0.

applied Mg may be more effective in decreasing the grass tetany ratio where soil Ca is low.

In both Maile and Wahiawa (B) soils, values of grass tetany ratio associated with pH 6.0 were significantly higher than those of pH 5.0 (Table 11). At the same time, values of the grass tetany ratio were higher in Wahiawa (B) than Maile soil at comparable pH level (Table 11).

The effect of applied K, Ca and Mg fertilizers and their combinations on concentrations of other plant nutrients of kikuyugrass

Phosphorus

Tissue P concentration was found to decrease progressively with increasing soil K in both soils although the extent of the decrease was greater in Wahiawa (B) than in Maile soil (Fig. 47). However, Tamimi et al (1968) reported an increase in tissue P concentration in kikuyugrass with increasing application of K in a field study on the Island of Hawaii. Tissue P concentration was consistently lower in the grass grown in Maile than in Wahiawa (B) soil. This may be due to the greater amount of total P in the former than in the latter soil since there was four times more soil per pot of Wahiawa (B) than Maile soil (2000g vs.500g/pot O.D.) as well as the greater P fixation capacity possessed by the Maile than Wahiawa (B) soils (Fox, 1974; Fox and Kamprath, 1970). Soil analysis performed at the end revealed

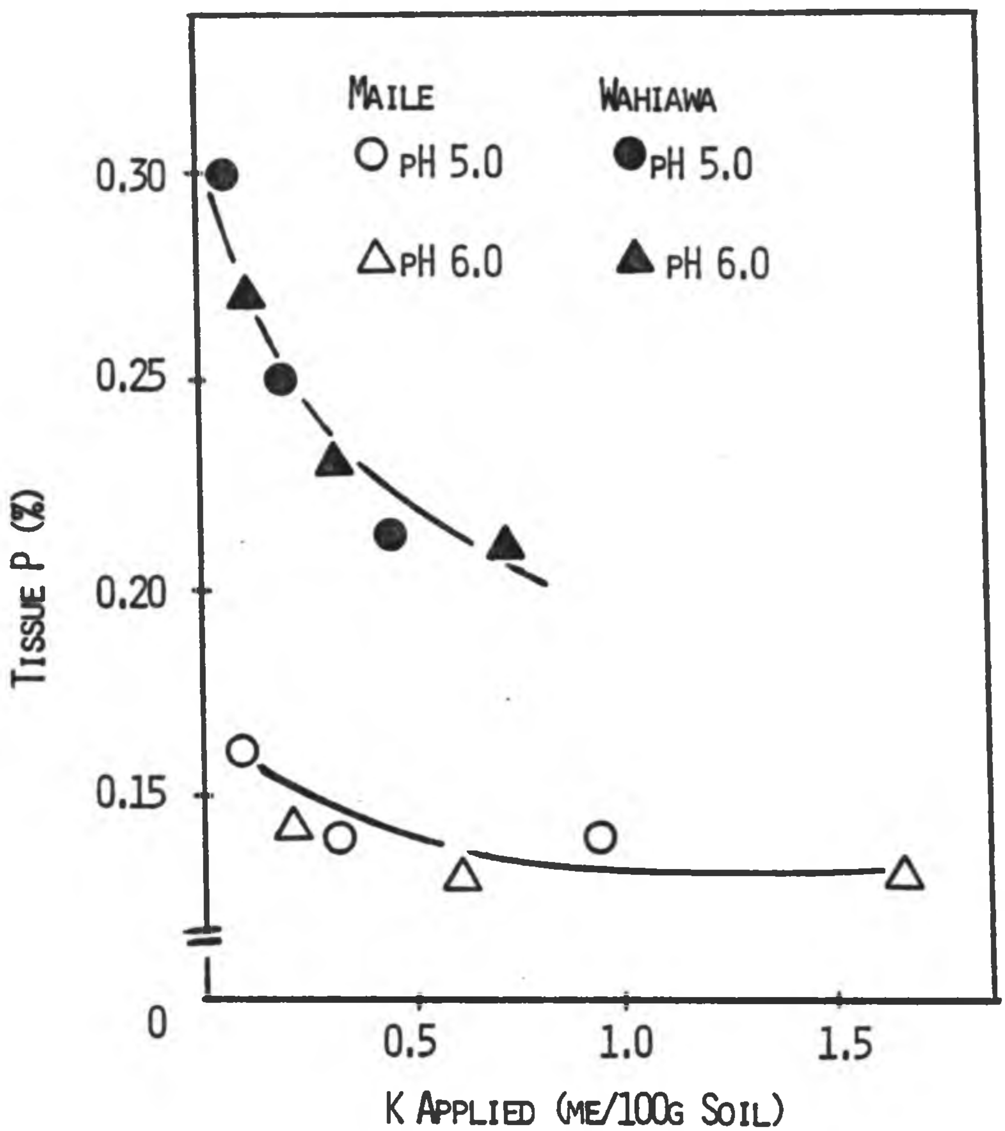

Fig. 47. Effect of applied K on tissue P concentration of kikuyugrass.

that extractable P was not affected by the applied K in both soils at the two pH levels (Table 23) thus reflecting that some mechanisms other than that of soil were responsible for such phenomenon.

Total P uptake showed an increasing trend in response to increasing applied K except in Wahiawa (B) soil at pH 6.0, where no significant effect was observed (Table 24).

The effect of applied Ca on tissue P concentration and total P uptake of kikuyugrass grown in both soils at the two pH levels are presented in Tables 25 and 26, respectively. Except that in Wahiawa (B) soil at pH 5.0, increasing soil Ca did not affect tissue P concentration significantly. Total P uptake by kikuyugrass grown in Maile soil soil was not affected by the applied Ca at both pH levels; in the case of Wahiawa (B) soil, increasing soil Ca increased the total P uptake at both pH levels.

The response of tissue P concentration and total P uptake to various rates of applied Mg in both soils is shown in Tables 27 and 28, respectively. Tissue P concentration was not affected significantly by increasing soil Mg at both pH levels in Maile soil; however, in Wahiawa (B) soil, tissue P concentration was enhanced by increasing soil Mg. Total P uptake by kikuyugrass increased with increasing applied Mg in both soils at both pH levels.

Table 23. Effect of applied K on soil extractable P in Maile and Wahiawa (B) soils at pH 5.0 and pH 6.0.

Level of K Applied	Extractable P (ppm) pH 5.0 Maile	pH 5.0 Wahiawa (B)	pH 6.0 Maile	pH 6.0 Wahiawa (B)
Low	25.4a +/	304a	25.4a	318a
Medium	25.7a	318a	25.8a	321a
High	24.9a	300a	24.0a	330a
	ns	ns	ns	ns

+/ Means in the same column followed by the same letter are not significantly different at 5% level determined by Duncan Multiple Range Test.

Table 24. Effect of applied K on total P uptake by kikuyugrass grown in Maile and Wahiawa (B) soils at pH 5.0 and pH 6.0.

Level of K Applied	Total P Uptake (mg/pot) pH 5.0 Maile	pH 5.0 Wahiawa (B)	pH 6.0 Maile	pH 6.0 Wahiawa (B)
Low	15.2b +/	28.2b	16.2b	39.6a
Medium	15.8b	31.7a	16.6b	37.6a
High	17.8a	33.1a	18.4a	40.3a
	**	*	**	ns

+/ Means in the same column followed by the same letter are not significantly different at 5% level determined by Duncan Multiple Range Test.

Table 25. Effect of applied Ca on P concentration of kikuyugrass grown in Maile and Wahiawa (B) soils at pH 5.0 and pH 6.0.

Level of Ca Applied	P concentration (%)			
	pH 5.0		pH 6.0	
	Maile	Wahiawa (B)	Maile	Wahiawa (B)
Low	0.15a +/	0.24c	0.13a	0.24a
Medium	0.15a	0.25b	0.13a	0.24a
High	0.14a	0.27a	0.14a	0.23a
	ns	**	ns	ns

+/ Means in the same column followed by the same letter are not significantly different at 5% level determined by Duncan Multiple Range Test.

Table 26. Effect of applied Ca on total P uptake by kikuyugrass grown in Maile and Wahiawa (B) soils at pH 5.0 and pH 6.0.

Level of Ca Applied	Total P Uptake (mg/pot) pH 5.0 Maile	pH 5.0 Wahiawa (B)	pH 6.0 Maile	pH 6.0 Wahiawa (B)
Low	16.2a +/	27.6b	16.6a	35.8b
Medium	16.3a	29.1b	17.0a	41.7a
High	16.3a	36.4a	17.6a	39.9a
	ns	**	ns	**

+/ Means in the same column followed by the same letter are not significantly different at 5% level determined by Duncan Multiple Range Test.

Table 27. Effect of applied Mg on P concentration of kikuyugrass grown in Maile and Wahiawa (B) soils at pH 5.0 and pH 6.0.

Level of Mg Applied	P concentration (%)			
	pH 5.0		pH 6.0	
	Maile	Wahiawa (B)	Maile	Wahiawa (B)
Low	0.15a +/	0.26b	0.14a	0.23b
Medium	0.15a	0.25c	0.14a	0.22c
High	0.15a	0.27a	0.14a	0.26a
	ns	**	ns	**

+/ Means in the same column followed by the same letter are not significantly different at 5% level determined by Duncan Multiple Range Test.

Table 28. Effect of applied Mg on total P uptake by kikuyugrass grown in Maile and Wahiawa (B) soils at pH 5.0 and pH 6.0.

Level of Mg Applied	Total P Uptake (mg/pot)			
	pH 5.0		pH 6.0	
	Maile	Wahiawa (B)	Maile	Wahiawa (B)
Low	15.6b+/	26.9c	16.6b	36.2b
Medium	16.2ab	31.2b	16.8b	37.5b
High	16.9a	34.7a	17.7a	43.7a
	**	**	*	**

+/ Means in the same column followed by the same letter are not significantly different at 5% level determined by Duncan Multiple Range Test.

A highly significant interaction between applied K and Ca on P concentration of kikuyugrass was observed in Wahiawa (B) soil at pH 5.0 (Fig. 48). The decrease in P concentration as a result of increasing applied K rate was retarded by raising soil Ca level.

The response of P concentration of kikuyugrass grown in Wahiawa (B) soil at pH 5.0 to applied Mg at various soil Ca levels is illustrated in Fig. 49. At low and medium Ca levels, tissue P concentration fluctuated with applied Mg levels; however, at high Ca rate, tissue P concentration increased significantly with increasing applied Mg.

Sulphur

Tissue S concentration in Kikuyugrass grown in Maile soil decreased with increasing soil K application at both pH levels (Fig. 50). Similar result was reported by Smith (1981). In Wahiawa (B) soil, tissue S content was lowered by increasing applied soil K at pH 5.0 but was not affected significantly at pH 6.0. Tissue S concentration, which was higher at pH 6.0 than at 5.0 in Wahiawa (B) soil was not affected significantly by soil pH in Maile soil.

In Maile soil, tissue S concentration of kikuyugrass was not affected significantly by soil Ca level at both pH levels (Table 29). In the case of Wahiawa (B) soil, tissue S content was enhanced by the application of Ca at pH 6.0 but no consistent trend was observed at pH 5.0.

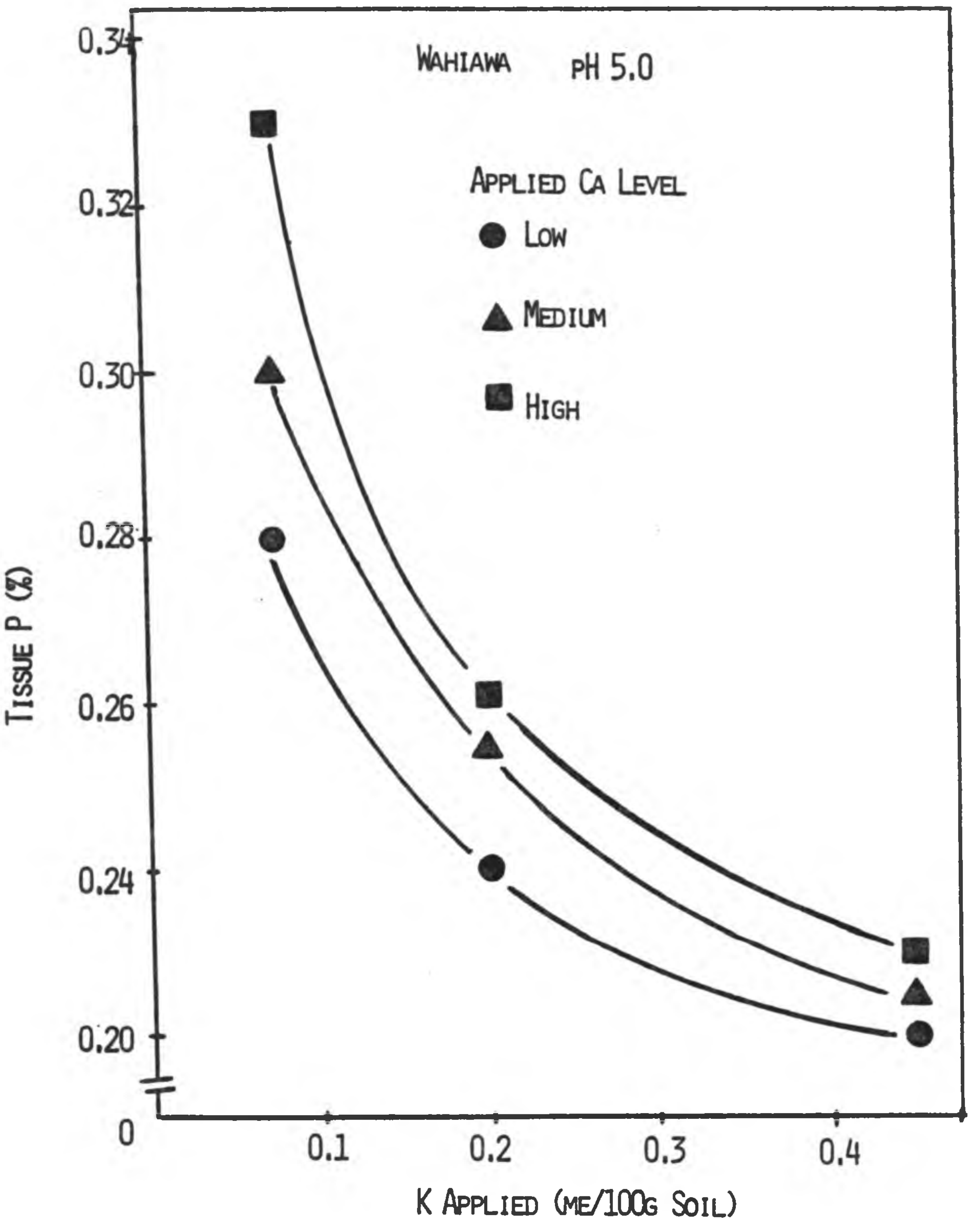

Fig. 48. Effect of applied K on tissue P concentration of kikuyugrass at various levels of applied Ca in Wahiawa (B) soil at pH 5.0.

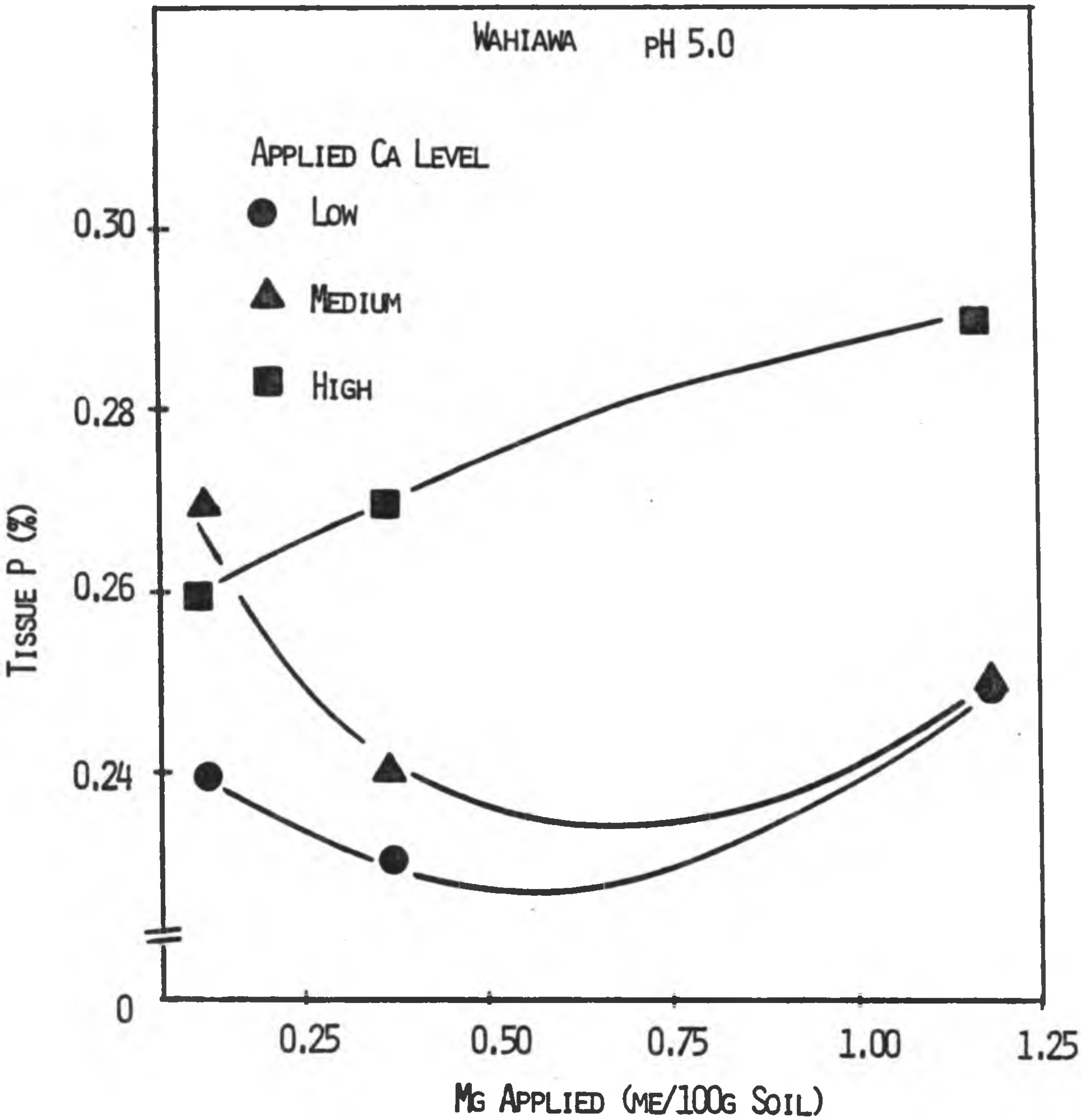

Fig. 49. Effect of applied Mg on tissue P concentration of kikuyugrass at various levels of applied Ca in Wahiawa (B) soil at pH 5.0.

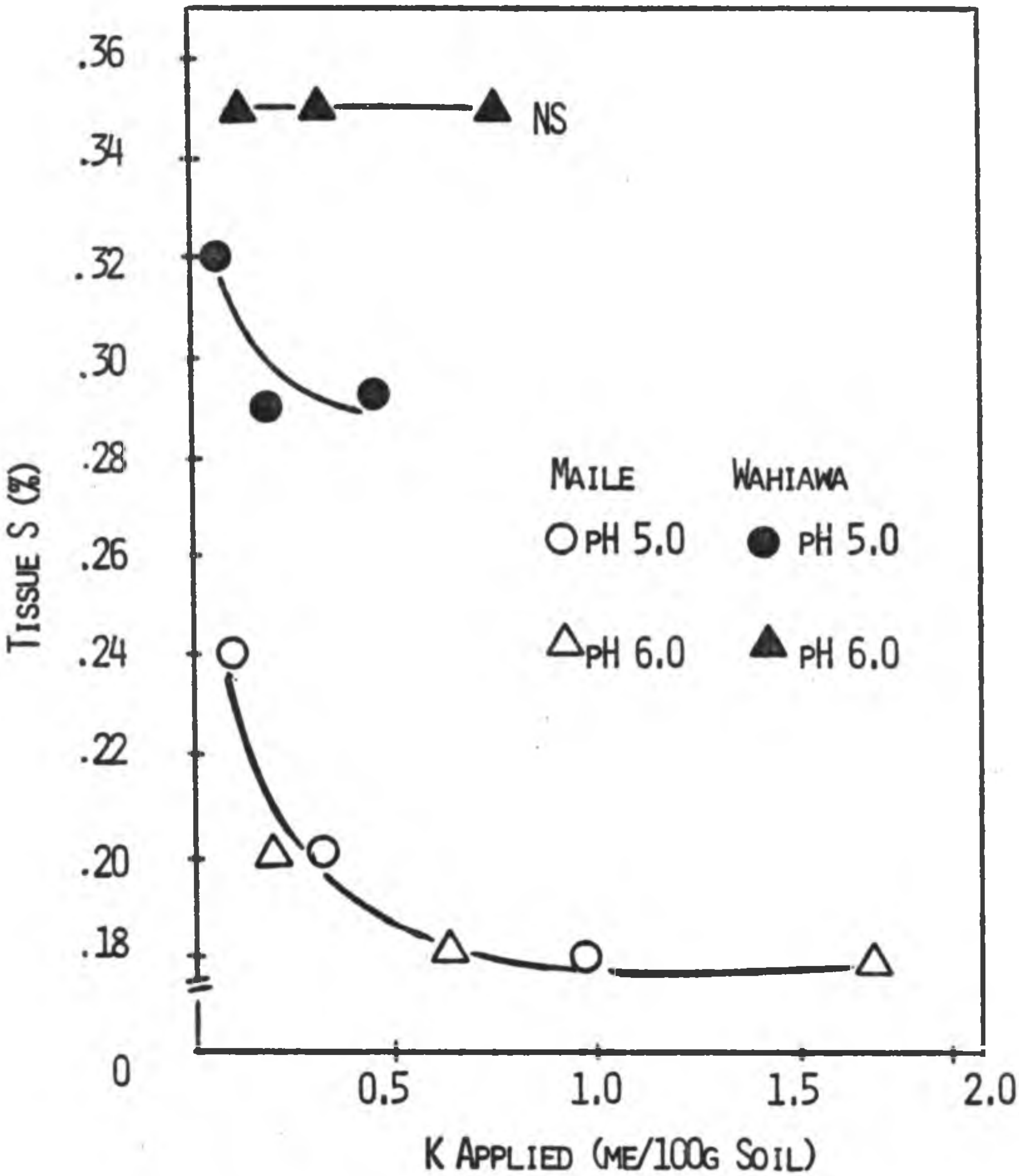

Fig. 50. Effect of applied K on tissue S concentration of kikuyugrass.

Table 29. Effect of applied Ca on S concentration of kikuyugrass grown in Maile and Wahiawa (B) soils at pH 5.0 and pH 6.0.

Level of Ca Applied	S Concentration (%) pH 5.0 Maile	S Concentration (%) pH 5.0 Wahiawa (B)	S Concentration (%) pH 6.0 Maile	S Concentration (%) pH 6.0 Wahiawa (B)
Low	0.20a+/	0.29b	0.19a	0.32c
Medium	0.21a	0.32a	0.19a	0.35b
High	0.21a	0.29b	0.19a	0.37a
	ns	**	ns	**

+/ Means in the same column followed by the same letter are not significantly different at 5% level determined by Duncan Multiple Range Test.

In both Maile and Wahiawa (B) soils, tissue S content increased with increasing applied Mg at pH 5.0 and 6.0 although the increase was more drastic in Wahiawa (B) than in Maile soil (Fig. 51). A higher S content was obtained at pH 6.0 than at 5.0 in Wahiawa (B) soil since more K was applied as potassium sufhate at the elevated soil pH; however, the reverse was the case for Maile soil.

A significant interaction between applied Ca and Mg on S concentration of kikuyugrass was found in Wahiawa (B) soil at pH 6.0 (Fig. 52). The increase in S concentration which was brought about by increasing applied Mg was further enhanced with increasing rates of applied Ca.

Interaction between applied K and Mg on S content of kikuyugrass was highly significant in Wahiawa (B) soil at both pH levels. At pH 5.0, when K was applied with low and high dosages of Mg, S concentration of kikuyugrass decreased with increasing applied K; however, at medium level of applied Mg, no consistent trend was observed on tissue S concentration (Fig. 53). At pH 6.0, tissue S content increased slightly with increasing soil K when Mg levels were low and medium; however, at high rate of applied Mg, tissue S concentration decreased significantly with increasing application of K fertilizer (Fig. 54).

At comparable pH levels, tissue S concentration was higher in the grass grown in Wahiawa (B) than Maile soil (Table 30).

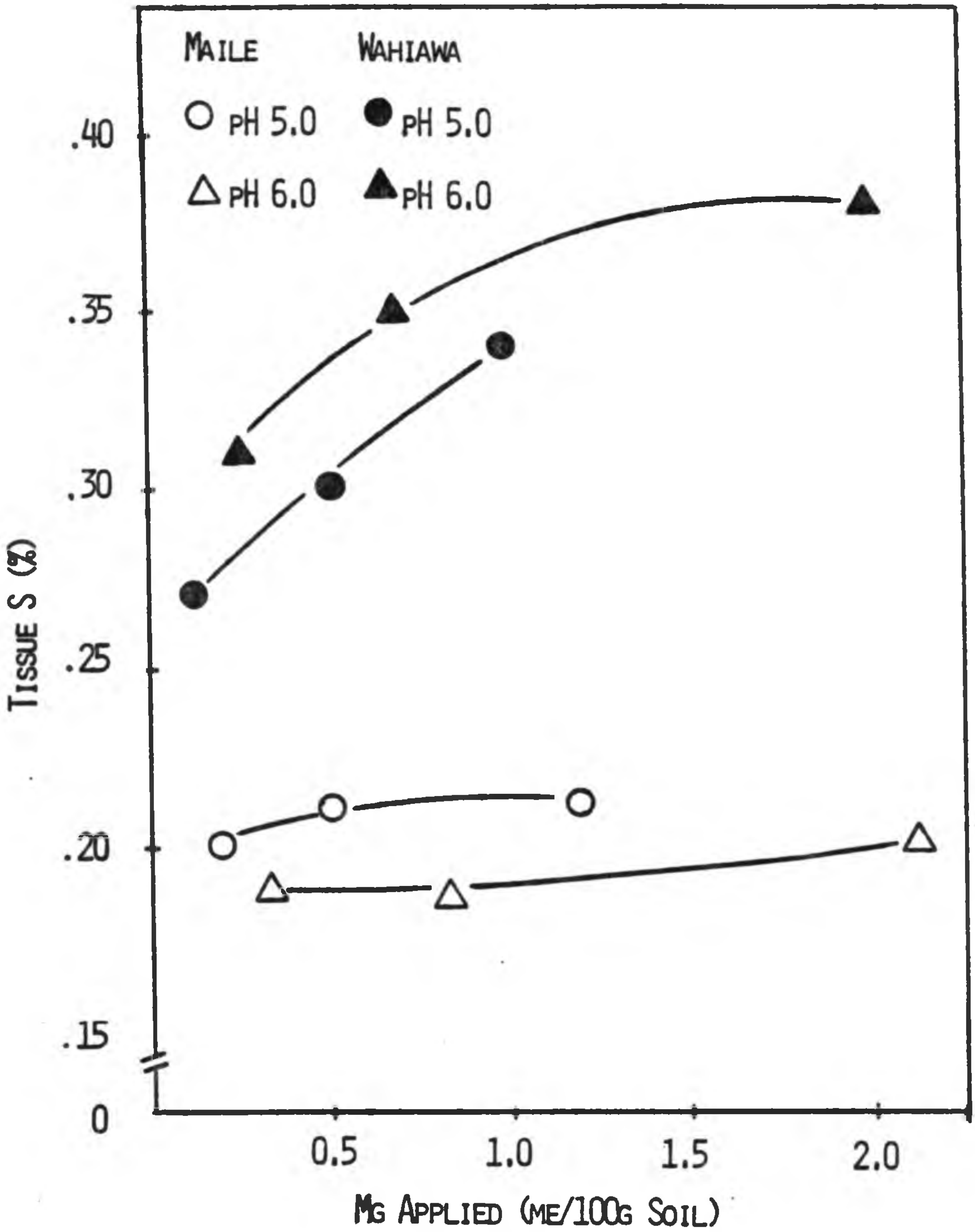

Fig. 51. Effect of applied Mg on tissue S concentration of kikuyugrass.

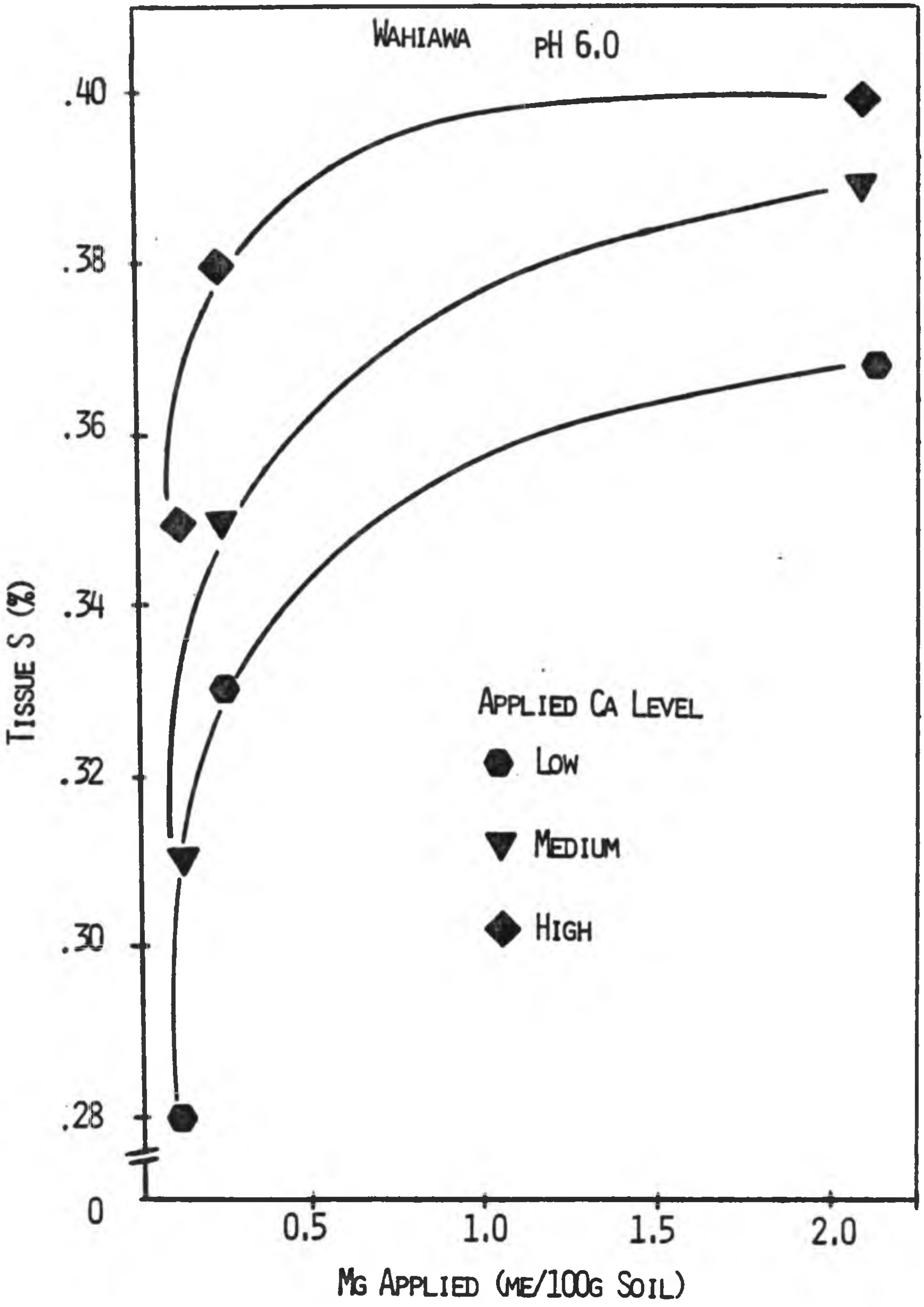

Fig. 52. Relationship between tissue S concentration and applied Mg in kikuyugrass at various levels of applied Ca in Wahiawa (B) soil at pH 6.0.

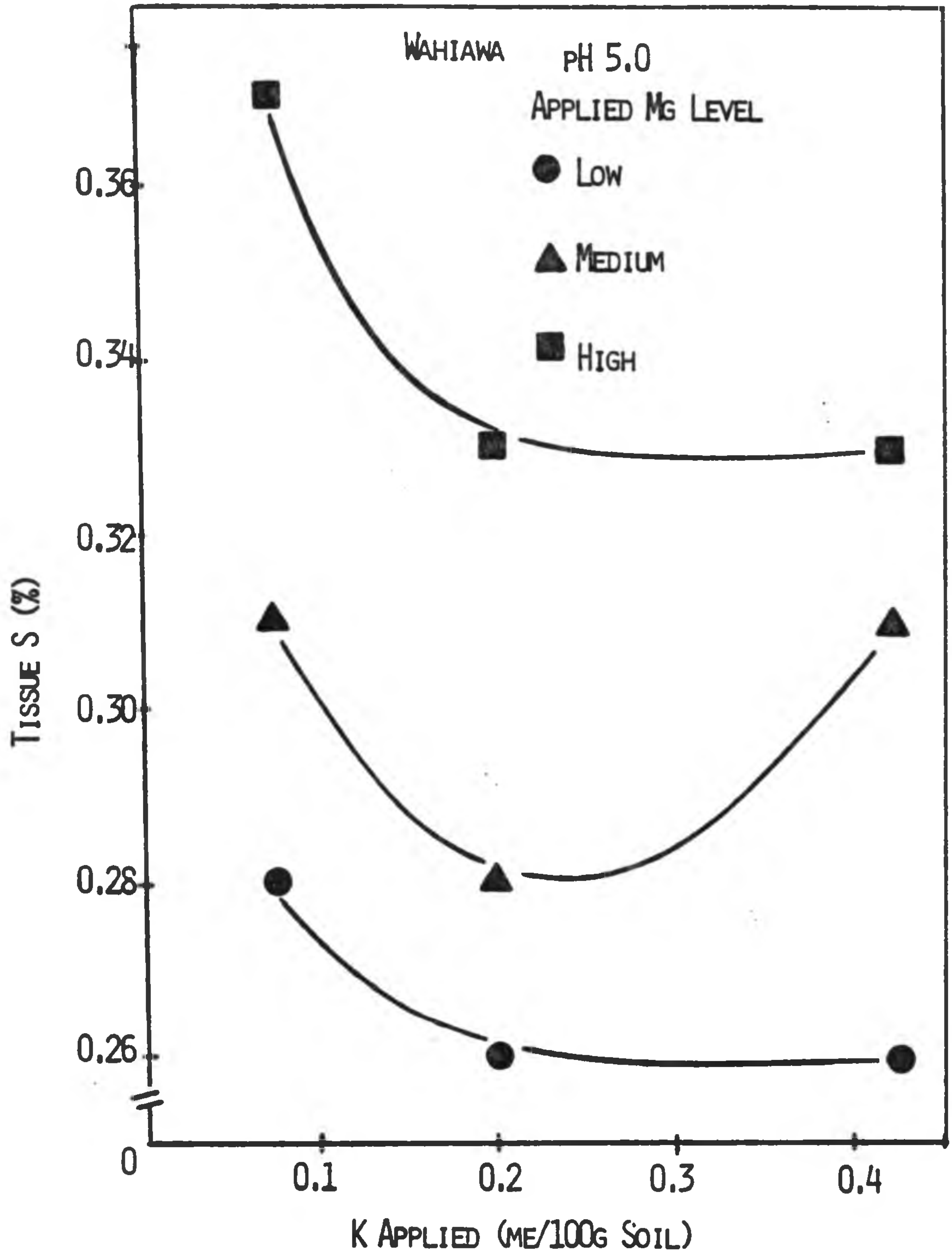

Fig. 53. Relationship between tissue S concentration and applied K in kikuyugrass at various levels of applied Mg in Wahiawa (B) soil at pH 5.0.

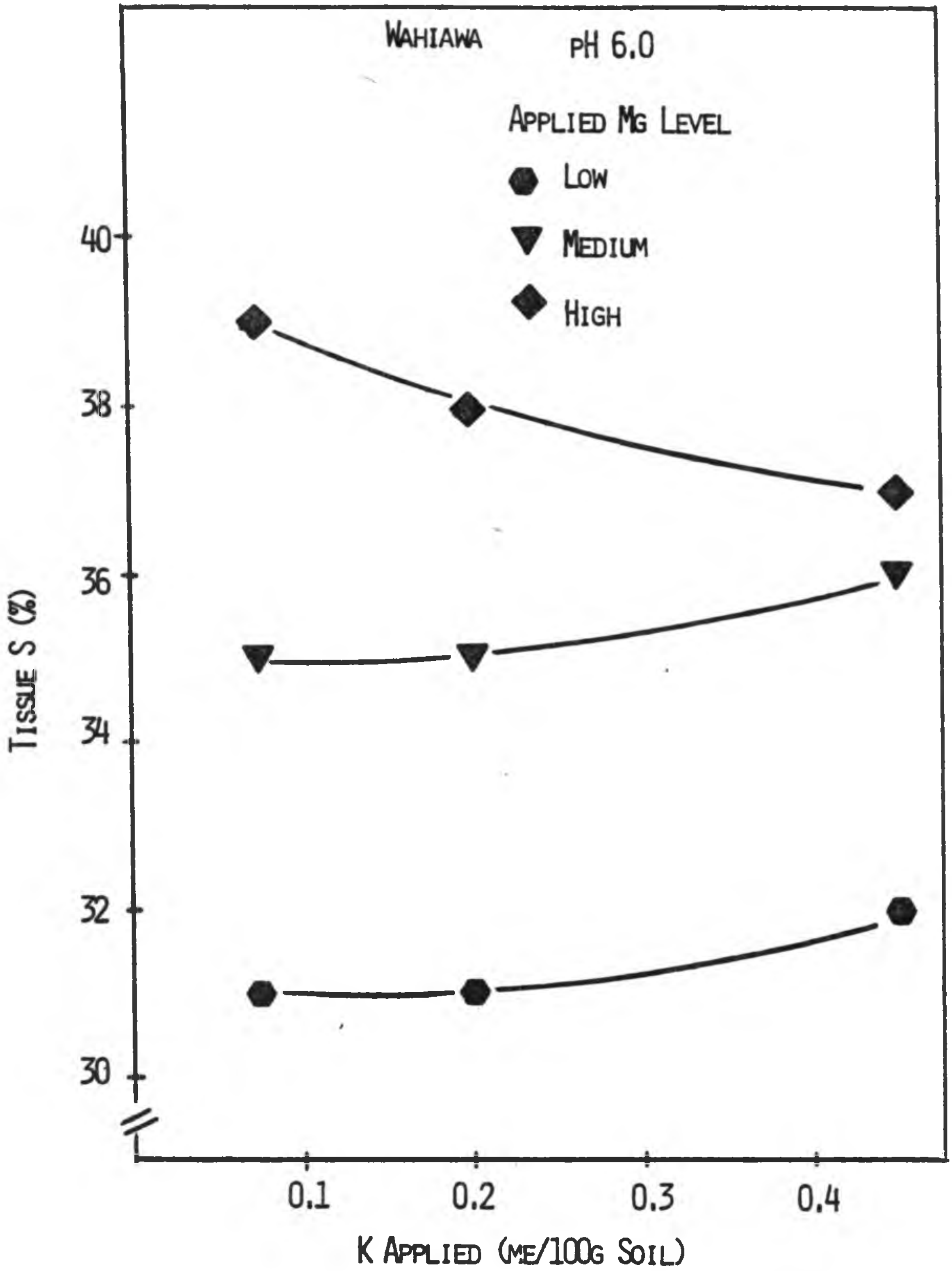

Fig. 54. Relationship between tissue S concentration and applied K in kikuyugrass at various levels of applied Mg in Wahiawa (B) soil at pH 6.0.

Table 30. Effect of soil pH on Zn, Cu and S concentrations of kikuyu-grass grown in Maile and Wahiawa (B) soils.

pH	Zn	Cu	S
	Mineral Concentration		
	----ppm----		%
		---Maile---	
5.0	52a +/	13a +/	0.21a +/
6.0	39b	13a	0.19b
	**	ns	**
		---Wahiawa--- (B)	
5.0	92a +/	18a +/	0.30b +/
6.0	52b	16b	0.35a
	**	**	**

+/ Means in the same column followd by the same letter are not significantly different at 5% level determined by Duncan Multiple Range Test.

Zinc

Tissue Zn concentration of kikuyugrass grown in both Maile and Wahiawa (B) soils decreased with increasing applied K rate at both pH 5.0 and pH 6.0 although such a decrease was more drastic in Wahiawa (B) than Maile soil (Fig. 55).

In Wahiawa (B) soil, tissue Zn content decreased significantly with increasing applied Ca at both pH levels. Similar response was also obtained in grass grown in Maile soil at pH 6.0; however, no consistent trend was obseverd at pH 5.0 (Table 31).

At pH 5.0, tissue Zn concentration of kikuyugrass grown in both Maile and Wahiawa (B) soils decreased with increasing Mg application (Table 32); however, at pH 6.0, a reverse situation was observed in both soils. The rate of applied Mg affected the behavior of tissue Zn concentration of kikuyugrass in Maile soil at pH 5.0. At low and medium levels of applied Mg, tissue Zn concentration decreased with increasing applied K; at a high level of soil Mg, increasing K rate caused an increase in tissue Zn content (Fig. 56).

There was a significant interaction between applied K and Ca on tissue Zn concentration of kikuyugrass grown in Wahiawa (B) soil at pH 5.0 (Fig. 57). At this pH, tissue Zn concentration of kikuyugrass decreased from increasing K rate at high soil Ca level (Fig. 57).

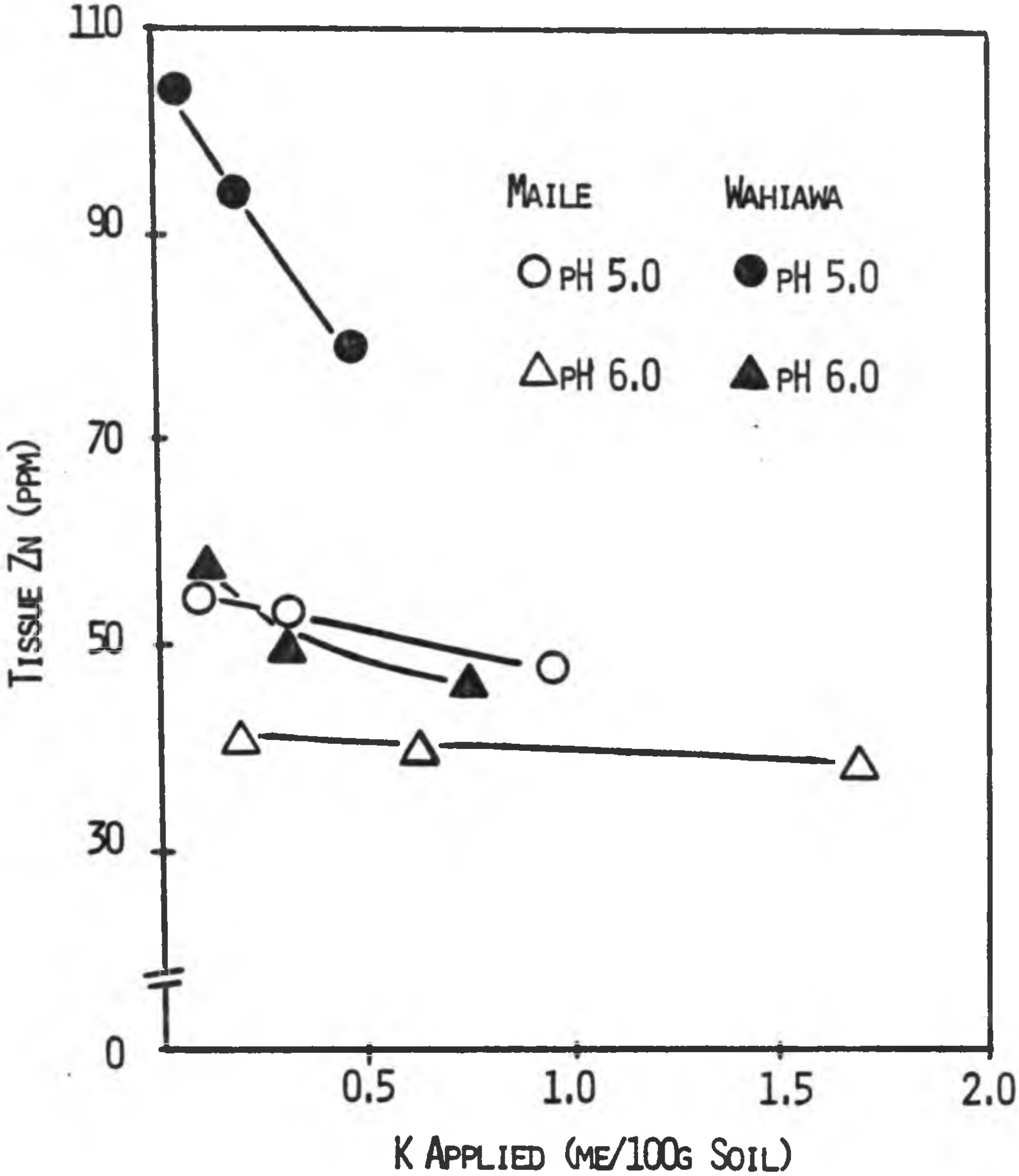

Fig. 55. Effect of applied K on tissue Zn concentration of kikuyugrass.

Table 31. Effect of applied Ca on Zn concentration of kikuyugrass grown in Maile and Wahiawa (B) soils at pH 5.0 and pH 6.0.

Level of Ca Applied	Zn Concentration (ppm) pH 5.0 Maile	pH 5.0 Wahiawa (B)	pH 6.0 Maile	pH 6.0 Wahiawa (B)
Low	51b +/	101a	40a	60a
Medium	55a	95b	38b	49b
High	50b	80c	38b	46c
	**	**	**	**

+/ Means in the same column followed by the same letter are not significantly different at 5% level determined by Duncan Multiple Range Test.

Table 32. Effect of applied Mg on Zn concentration of kikuyugrass grown in Maile and Wahiawa (B) soils at pH 5.0 and pH 6.0.

Level of Mg Applied	Zn Concentration (ppm) pH 5.0 Maile	pH 5.0 Wahiawa (B)	pH 6.0 Maile	pH 6.0 Wahiawa (B)
Low	55a +/	102a	39c	51b
Medium	52b	93b	38b	51b
High	48c	81c	40a	53a
	**	**	**	**

+/ Means in the same column followed by the same letter are not significantly different at 5% level determined by Duncan Multiple Range Test.

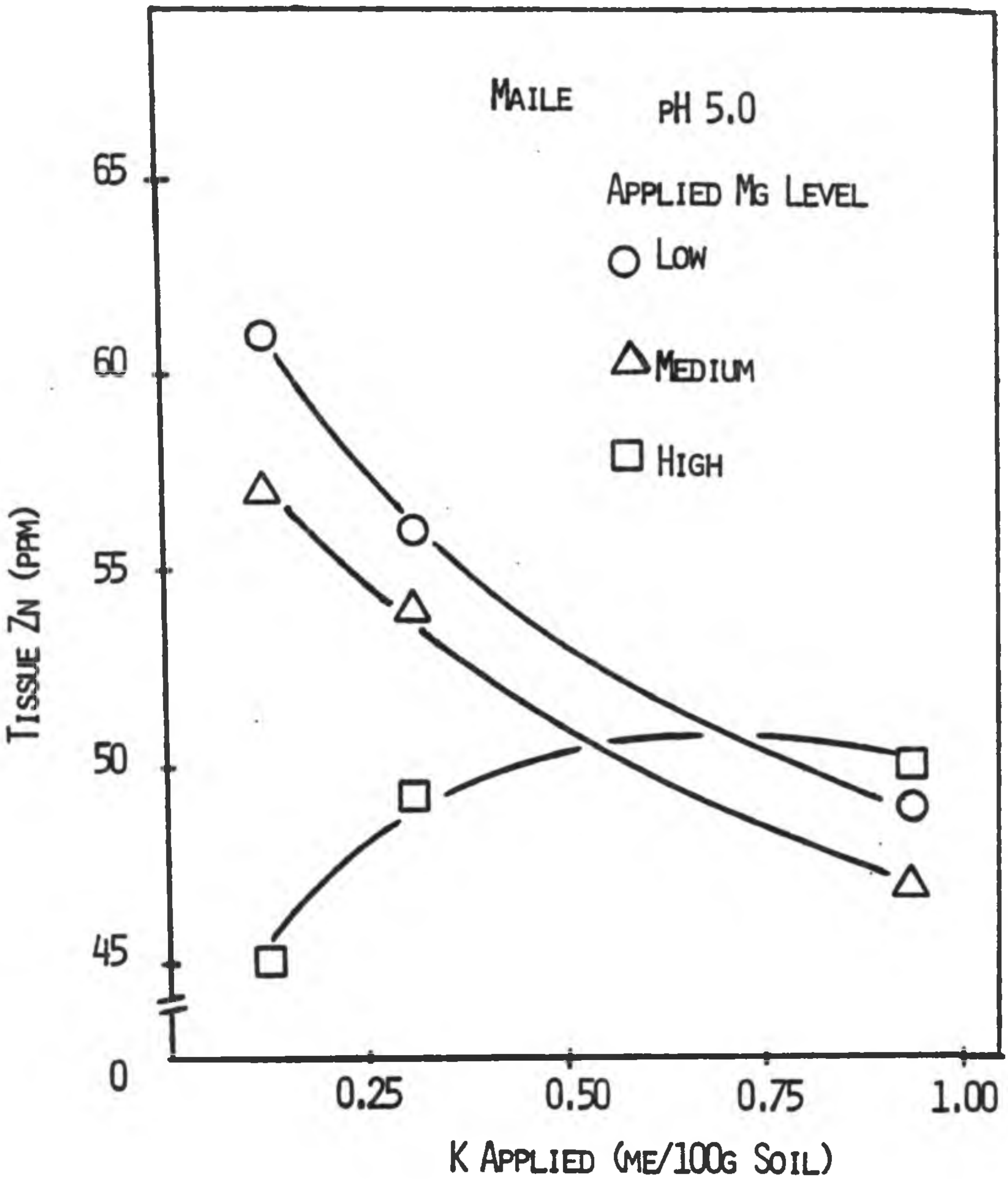

Fig. 56. Relationship between applied K and tissue Zn concentration in kikuyugrass at various levels of applied Mg in Maile soil at pH 5.0.

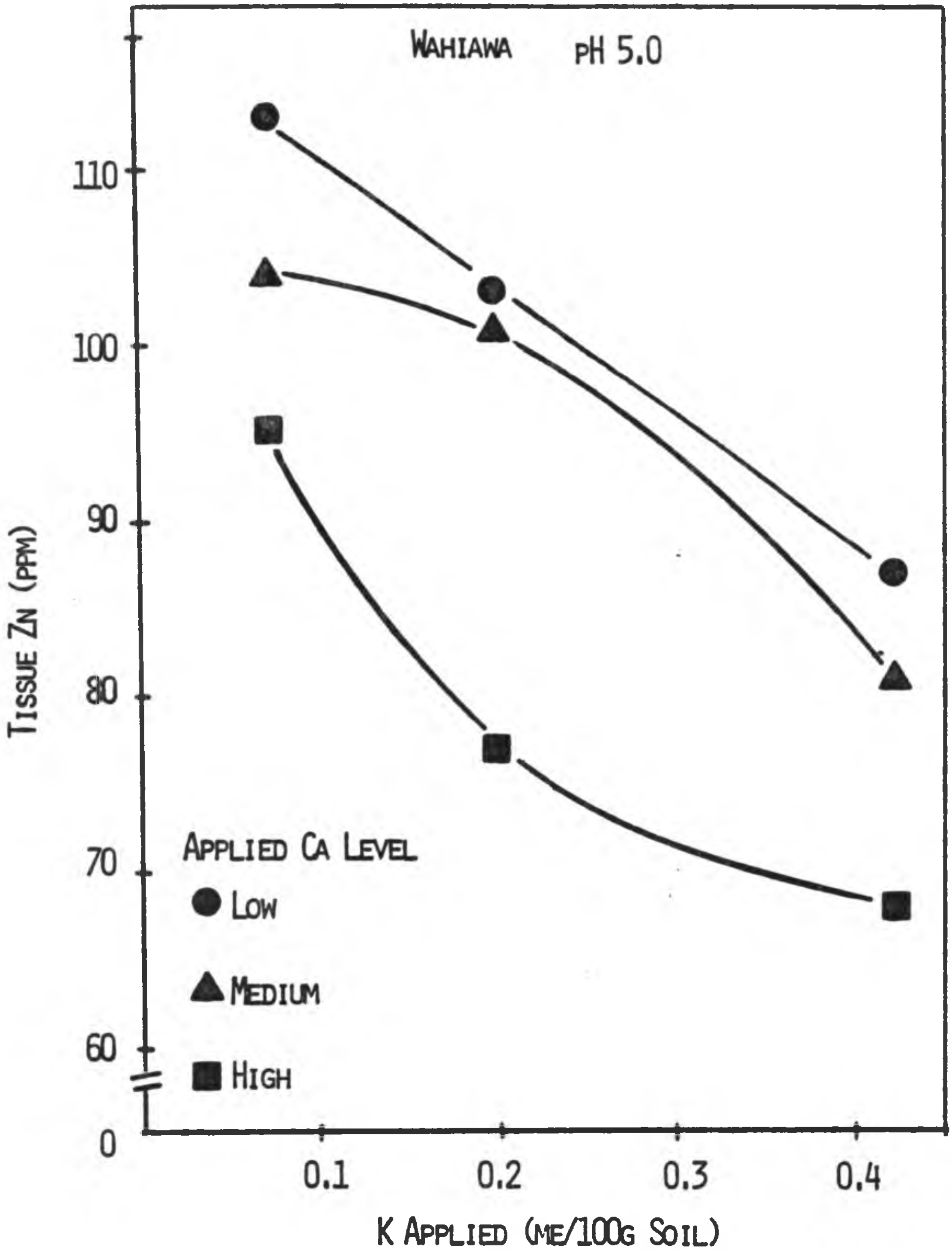

Fig. 57. Relationship between applied K and tissue Zn concentration in kikuyugrass at various levels of applied Ca in Wahiawa (B) soil at pH 5.0.

The response of tissue Zn concentration of kikuyugrass to both applied Ca and Mg in Wahiawa soil at both pH 5.0 and 6.0 are shown in Figs. 58 and 59, respectively. At pH 5.0, in the presence of low and medium levels of applied Ca, tissue Zn concentration decreased with increasing Mg application; however, no consistent trend was observed between these 2 parameters when a high rate of Mg was applied. At pH 6.0, when the soil Ca level was low, tissue Zn concentration increased with increasing application of Mg. At medium level of soil Ca rate, tissue Zn content was not affected significantly by applied Mg. At high Ca rate, tissue Zn content in response to the applied Mg was not consistent. At any given rate of applied Mg and at both pH levels, tissue Zn concentration was greater when Ca level was lower.

In both soils, tissue Zn concentration of kikuyugrass was higher at pH 5.0 than at 6.0. This may due to the reduced Zn availability in the soil at higher soil pH. Kikuyugrass grown in Wahiawa (B) soil had higher tissue Zn content when compared to that of Maile soil at comparable pH level (Table 30).

Copper

Tissue concentration of Cu in kikuyugrass grown in Maile soil increased significantly with increasing K applied at both soil pH levels (Table 33); in the case the Wahiawa (B) soil, it was depressed by an increase in the applied K at both pH levels.

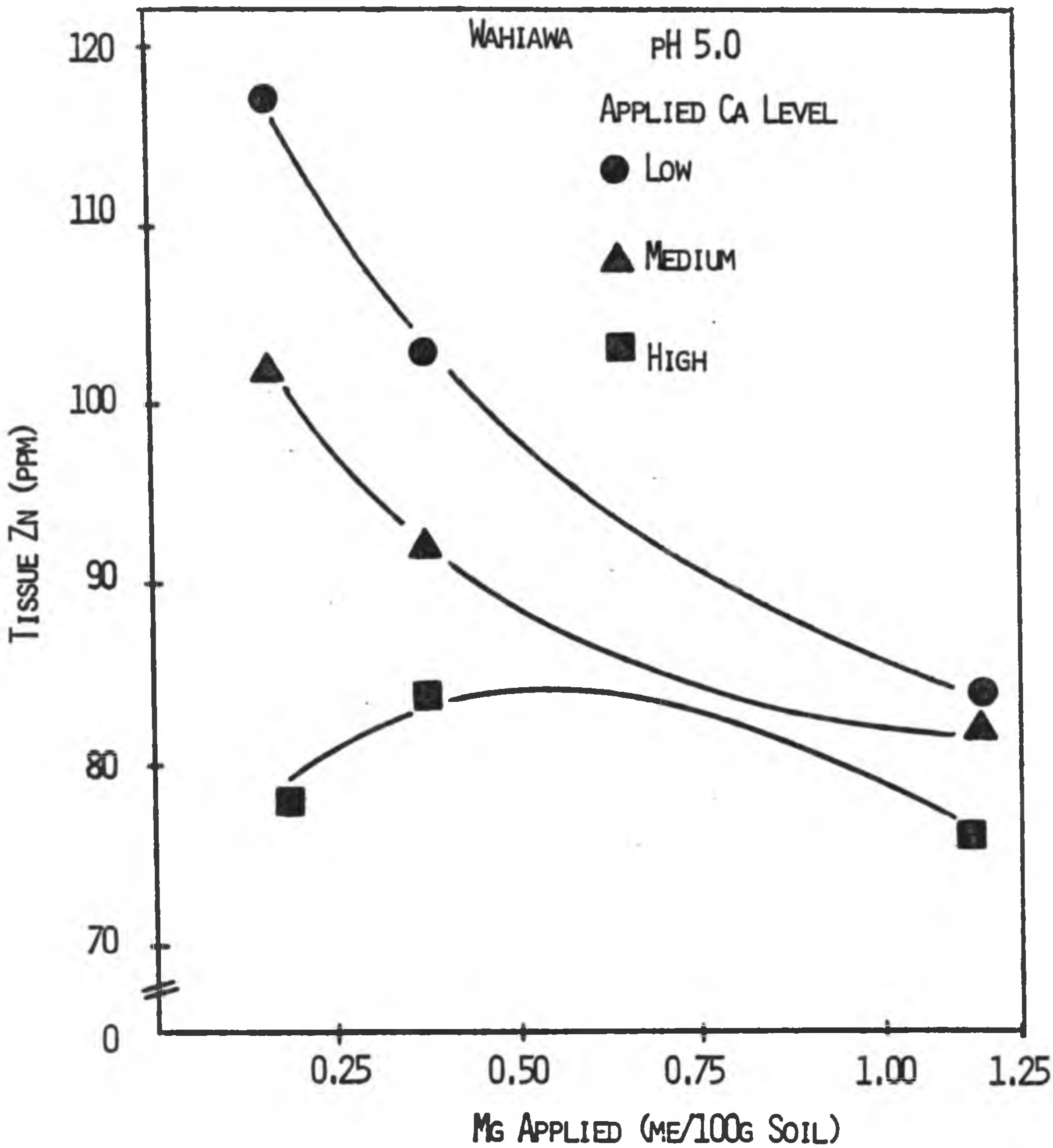

Fig. 58. Relationship between applied Mg and tissue Zn concentration in kikuyugrass at various levels of applied Ca in Wahiawa (B) soil at pH 5.0.

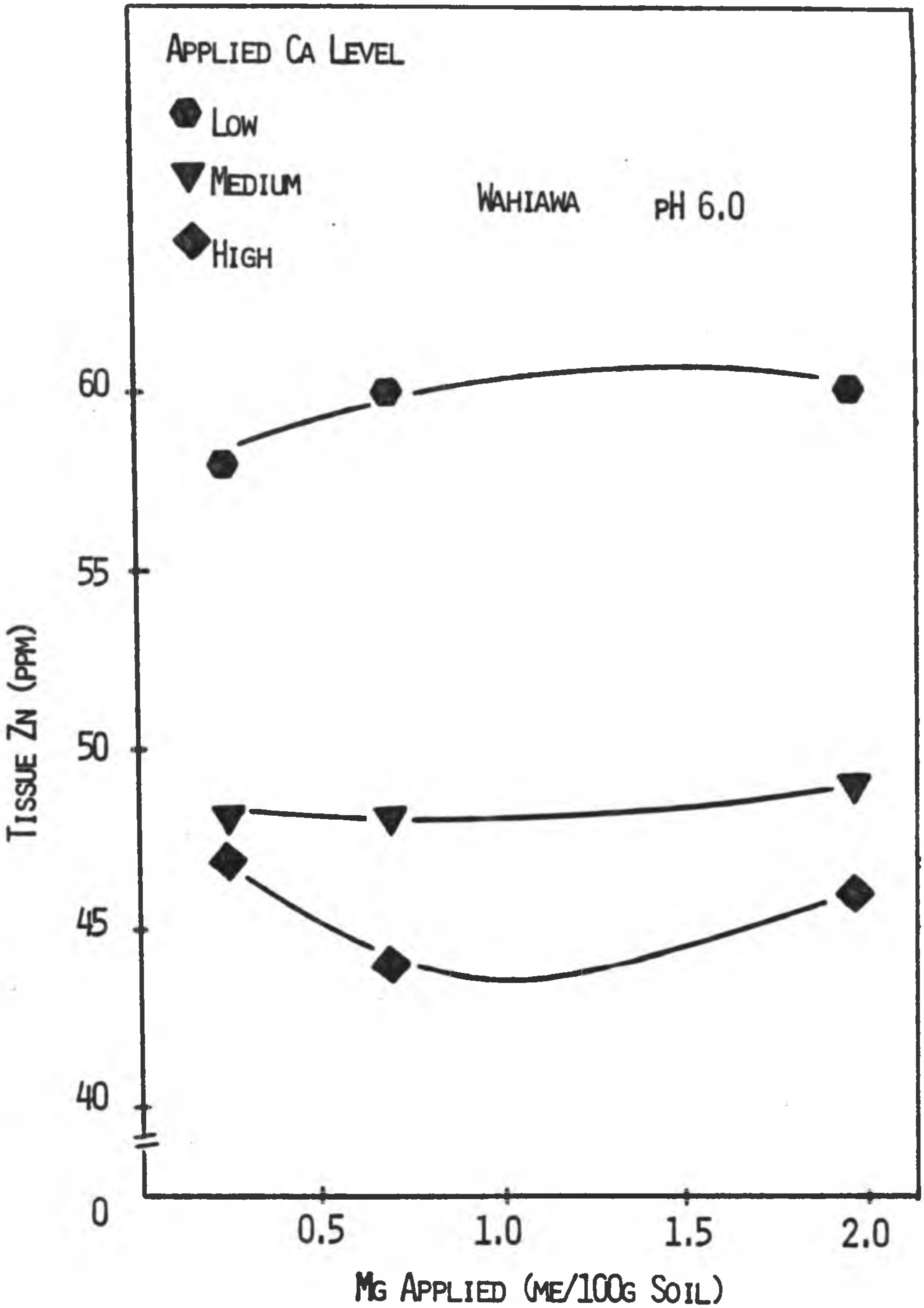

Fig. 59. Relationship between applied Mg and tissue Zn concentration in kikuyugrass at various levels of applied Ca in Wahiawa (B) soil at pH 6.0.

Table 33. Effect of applied K on Cu concentration of kikuyugrass grown in Maile and Wahiawa (B) soils at pH 5.0 and pH 6.0.

Level of K Applied	Cu Concentration (ppm)			
	pH 5.0		pH 6.0	
	Maile	Wahiawa (B)	Maile	Wahiawa (B)
Low	12b +/	18a	12c	16a
Medium	13a	18a	13b	16a
High	13a	17b	14a	15b
	**	**	**	**

+/ Means in the same column followed by the same letter are not significantly different at 5% level determined by Duncan Multiple Range Test.

Soil Ca did not seem to influence the tissue Cu concentration of kikuyugrass grown in Maile soil at both pH 5.0 and 6.0 (Table 34); in the case of Wahiawa (B) soil, it was decreased by an increase in the application of Ca at both pH levels.

At both pH levels, tissue Cu concentration of kikuyugrass was not affected significantly by the Mg rates applied to Maile soil (Table 35). On the other hand, tissue Cu concentration of kikuyugrass grown in Wahiawa (B) soil increased with increasing applied Mg at both pH levels. In Maile soil, tissue Cu concentration was not significantly different between pH 5.0 and 6.0; in Wahiawa (B) soil, however, it was higher at pH 5.0 than at pH 6.0 (Table 30).

<u>Relationship between various nutrient concentrations of kikuyugrass</u>

Linear regression analyses were employed to determine the relationship between various nutrient concentrations in kikuyugrass and the results are presented in Table 36. Tissue concentrations of Ca, Mg and P correlated negatively with tissue K concentrations in both Maile and Wahiawa (B) soils. Tissue Mg and P concentrations correlated positively with tissue Ca concentration in both soils and and the corresponding R values were significant at $P<0.01$. Phosphorus concentration also correlated positively with tissue Mg concentration in both soils.

Table 34. Effect of applied Ca on Cu concentration of kikuyugrass grown in Maile and Wahiawa (B) soils at pH 5.0 and pH 6.0.

Level of Ca Applied	Cu Concentration (ppm) pH 5.0 Maile	pH 5.0 Wahiawa (B)	pH 6.0 Maile	pH 6.0 Wahiawa (B)
Low	13a +/	18a	13a	16a
Medium	13a	19a	13a	15b
High	13a	17b	13a	15b
	ns	**	ns	*

+/ Means in the same column followed by the same letter are not significantly different at 5% level determined by Duncan Multiple Range Test.

Table 35. Effect of applied Mg on Cu concentration of kikuyugrass grown in Maile and Wahiawa (B) soils at pH 5.0 and pH 6.0.

Level of Mg Applied	Cu Concentration (ppm) pH 5.0 Maile	pH 5.0 Wahiawa (B)	pH 6.0 Maile	pH 6.0 Wahiawa (B)
Low	13a +/	17b	13a	16b
Medium	12a	17b	13a	15b
High	13a	19a	13a	17a
	ns	**	ns	**

+/ Means in the same column followed by the same letter are not significantly different at 5% level determined by Duncan Multiple Range Test.

Table 36. Relationships between various nutrient concentrations of kikuyugrass grown in Maile and Wahiawa (B) soils.

Parameter	Soil	Equation	N(*)	R
%Ca vs. %K	Maile	%Ca = -0.08709%K + 0.5569	54	-0.83**
%Ca vs. %K	Wahiawa (B)	%Ca = -0.08416%K + 0.8115	54	-0.80**
%Mg vs. %K	Maile	%Mg = -0.1468%K + 0.7324	54	-0.77**
%Mg vs. %K	Wahiawa (B)	%Mg = -0.11225K + 1.0043	54	-0.75**
%Mg vs. %Ca	Maile	%Mg = 0.7124%Ca + 0.1491	54	0.39**
%Mg vs. %Ca	Wahiawa (B)	%Mg = 0.6690%Ca + 0.2562	54	0.47**
%P vs. %K	Maile	%P = -0.0078%K + 0.1579	54	-0.62**
%P vs. %K	Wahiawa (B)	%P = -0.0208%K + 0.3234	54	-0.77**
%P vs. %Ca	Maile	%P = 0.0824%Ca + 0.1108	54	0.69**
%P vs. %Ca	Wahiawa (B)	%P = 0.1465%Ca + 0.1734	54	0.59**
%P vs. %Mg	Maile	%P = 0.0320%Ca + 0.1278	54	0.49**
%P vs. %Mg	Wahiawa (B)	%P = 0.1220%Ca + 0.1747	54	0.68**

(*) No. of observations.

SUMMARY AND CONCLUSIONS

The differential adsorption of K, Ca and Mg by three tropical soils at pH 5.0 and 6.0 was established at 25 C. The three soils were Maile, Hawi and Wahiawa series representing an Inceptisol, a Mollisol and an Oxisol, respectively. The cationic strength of the equilibrating solution containing cationic pairs of K:Ca, K:Mg and Mg:Ca in the chloride salts of these three elements, was maintained at 0.1 N concentration. Cationic ratios of 1:1. 1:2, 1:4 and 1:8 were investigated. Equilibrium was achieved over 12 day period.

When equilibrating in 0.1 N solution of chloride of of K, Ca and Mg, the three soils adsorbed more K, Ca and Mg at pH 6.0 than at pH 5.0. This is due to pH dependent charges which these soils have. In the three soils at both pH levels, the amount of adsorbed cations was in the following order:

$$Ca > Mg > K$$

The Maile and Hawi series, being high in cation exchange capacity, selectively adsorbed divalent cations (Ca and Mg) over monovalent cation (K) at both pH levels. Moreover, between divalent cations, Ca was preferentially adsorbed over Mg by the two soils. The Wahiawa soil which is dominated by kaolinitic materials, mica and illite, is relatively low in cation exchange capacity, preferentially adsorbed monovalent cation (K) over divalent cations (Ca and Mg). Between Ca and Mg, Wahiawa soil preferentially adsorbed Ca over Mg. Preferential adsorption of K when in pair with Ca or Mg seems to be reduced in all soils as its relative concentration increased. Potassium seemed to be preferentially adsorbed with higher C value at pH 6.0 than at pH 5.0 when existed together with Ca. When with Mg, the differential adsorption of Ca seemed to be less at pH 6.0 than at pH 5.0 as indicated by a higher C value at the elevated pH level.

The preferential adsorption of an ion over the other by a soil is dependent upon the charge and its nature as well as the hydration radius of the ion involved, soil mineralogy, cation exchange capacity of the soil, soil pH and soil organic matter content.

Hence the preferential adsorption of K, Ca and Mg by the three soils at both pH levels was found to be in the following order:

Maile	Ca > Mg > K
Hawi	Ca > Mg > K
Wahiawa	K > Ca > Mg

The response of the dry matter production, mineral uptake and concentration of kikuyugrass as affected by various levels of applied K, Ca and Mg was investigated on two soils at two pH levels. The two soils were Maile and Wahiawa series, representing an Inceptisol and an Oxisol, respectively. The two pH levels were 5.0 and 6.0. The greenhouse experiment was a factorial design for KxCaxMg (3x3x3) with three replicates.

The total dry matter yield of kikuyugrass was increased by increasing applied K in both soils at the two pH levels. The increase in uptake and concentration of K in the tissue of kikuyugrass brought about by increasing application of K was not affected by the pH in both soils. Tissue K concentration associated with the maximum yield was determined to be 3.8% for Maile soil, however, such value was not determined for Wahiawa soil. Total dry matter yield in Wahiawa soil was significantly increased by increasing applied Ca at both pH levels; however, in the case of Maile soil, it was not significantly affected. In general, the application of Mg to both soils increased the dry matter yield of kikuyugrass at both pH levels.

The total uptake as well as concentrations of Ca and Mg increased with increasing applied Ca and Mg, respectively. The concentrations of Ca and Mg in tissue were higher at pH 5.0 than at pH 6.0 6.0 although higher concentrations of Ca and Mg were at the elevated soil pH in both soils.

Tissue Ca concentration of kikuyugrass grown in both soils decreased significantly with increasing applied K and Mg. The application of K to both soils depressed the tissue Mg concentration; however, soil Ca possessed no apparent effect on the tissue Mg concentration of kikuyugrass grown in both soils.

The application of Mg as well as Ca to both soils did not produce any significant effect on the tissue K concentration of kikuyugrass grown at the two pH levels.

The grass tetany ratio of kikuyugrass grown in the two soils increased with increasing soil K. This increase was enhanced by a lowering of the applied Mg level. In general, applied Ca did not have a significant effect on the grass tetany ratio of kikuyugrass grown in both Maile and Wahiawa soils. Meanwhile higher rates of Mg caused a drop in the grass tetany ratio.

A compromise has to be made between forage quality and forage quantity. An increase in dry matter yield can be achieved by applying high rates of K fertilizer to the soil which in turn also increases tissue K concentration, thus causing a decline in the forage quality through a rise in the grass tetany ratio. Such situation can be mended either by avoiding the usage of high rate of K fertilizer or utilizing high dosage of both K and Mg in the fertilization program so that not only the dry matter yield of the grass would be increased, but also the grass tetany ratio would be stabilized which otherwise would be raised in the absence of high soil Mg. At the same time, the benefit of using low rate of K fertilizer has also been demonstrated in a field study by Smith (1978) on green panic, revealing that levels of trans-aconitate, an organic anion believed to cause the development of grass tetany in ruminant animals, could be reduced by lowering the K application.

Concentrations of P, S and Zn in tissue of kikuyugrass decreased with increasing K in the two soils at both pH levels. The effect of soil K on tissue P concentration was not influenced by soil pH levels in both Maile and Wahiawa soils. Similar situation was observed in the tissue S level of kikuyugrass grown in Maile soil. Sulfur concentration in tissue of kikuyugrass grown in both soils increased with increasing soil Mg at both pH 5.0 and 6.0.

An attempt was made to relate the preferential adsorption of K, Ca and Mg by Maile and Wahiawa soil colloids to the uptake of these three cations by kikuyugrass grown in these soils. However, this effort was not successful due to the complications of the no leaching condition maintained in the greenhouse study and due to the cation exchange capacity possessed by roots of the kikuyugreass which enables it to have its own selectivity for these three cations.

APPENDIX

Table 37. Amount of chloride salts of potassium, calcium and magnesium required to prepare 0.1 N solution with various cationic ratios.

Cationic Ratio	Amount of Chloride Salts Used */ K:Ca	K:Mg	Mg:Ca
	------------ g/liter -----------		
0:1	0.00:5.55	0.0:10.17	0.00:5.55
1:0	7.46:0.00	7.46:0.00	10.17:0.0
1:1	3.73:2.78	3.73:5.09	5.09:2.78
1:2	2.46:3.73	2.46:6.81	3.35:3.73
1:4	1.47:4.44	1.47:8.13	2.03:4.44
1:8	0.82:4.94	0.82:9.05	1.12:4.94

*/ Chloride salts used were potassium chloride (mol.wt=74.56), calcium chloride (mol.wt=111.0) and magnesium chloride (mol.wt=203.3).

Table 38. Adsorption of K, Ca and Mg from solutions of various cationic ratios by Maile, Hawi and Wahiawa (A) soils at pH 5.0 and pH 6.0.

Cation Pair	pH 5.0 1:1	1:2	1:4	1:8	pH 6.0 1:1	1:2	1:4	1:8
				Maile				
K:Ca a/	0.536	0.303	0.167	0.064	1.697	1.195	0.767	0.495
	1.425	1.974	2.307	2.684	1.986	2.076	2.812	3.439
K:Mg b/	0.902	0.506	0.224	0.124	0.527	0.462	0.404	0.269
	1.041	1.608	1.977	2.250	1.411	1.682	2.128	2.922
Mg:Ca c/	0.544	0.467	0.216	0.096	1.238	0.636	0.361	0.129
	1.249	2.016	2.193	2.769	1.721	2.202	2.580	2.968
				Hawi				
K:Ca	1.117	0.761	0.695	0.451	1.325	0.928	0.643	0.466
	5.152	5.123	5.441	4.781	3.846	4.262	4.634	4.762
K:Mg	1.505	0.788	0.591	0.456	0.950	0.770	0.693	0.536
	2.754	3.089	3.365	3.582	2.629	3.072	3.311	4.520
Mg:Ca	1.437	0.728	0.430	0.188	1.240	0.856	0.404	0.167
	3.071	3.688	4.412	4.202	3.313	3.847	4.470	4.550
				Wahiawa (A)				
K:Ca	0.937	0.458	0.351	0.236	1.280	0.915	0.747	0.477
	0.819	1.119	1.254	1.609	0.679	0.738	1.054	1.207
K:Mg	0.547	0.308	0.295	0.218	0.517	0.472	0.417	0.269
	0.364	0.615	0.900	1.033	0.638	0.780	1.167	1.412
Mg:Ca	0.043	0.043	0.043	0.043	0.418	0.209	0.098	0.085
	0.580	1.236	1.372	1.410	0.951	1.220	1.282	1.372

a/ Ratio of K adsorbed to Ca adsorbed (cation adsorption expressed in me/100g).
b/ Ratio of K adsorbed to Mg adsorbed (cation adsorption expressed in me/100g)
c/ Ratio of Mg adsorbed to Ca adsrobed (cation adsorption expressed in me/100g)

Table 39. Mineral composition, dry matter yield and grass tetany ratio of kikuyugrass grown in Maile soil at pH 5.0 and pH 6.0.

Trt	CaMgK	DM a/ (g)	P (%)	K (%)	Ca (%)	Mg (%)	R b/	DM (g)	P (%)	K (%)	Ca (%)	Mg (%)	R
		pH 5.0						pH 6.0					
1	L L L	2.30	.16	.93	.56	.35	.42	2.76	.13	1.23	.47	.39	.56
2	L L M	2.36	.14	2.00	.41	.24	1.29	3.28	.13	2.50	.35	.25	1.65
3	L L H	3.03	.14	3.06	.26	.17	2.88	3.36	.13	3.43	.26	.15	3.44
4	L M L	2.33	.16	.84	.46	.66	.28	2.68	.14	1.30	.43	.60	.47
5	L M M	2.87	.14	1.72	.37	.49	.76	3.43	.12	2.47	.32	.34	1.43
6	L M H	3.23	.13	2.97	.26	.28	2.07	3.59	.13	3.43	.25	.21	2.94
7	L H L	2.82	.15	.86	.37	.74	.28	2.91	.14	1.21	.36	.75	.38
8	L H M	3.04	.13	1.65	.30	.61	.65	3.14	.14	2.76	.29	.45	1.36
9	L H H	3.58	.14	2.92	.25	.37	1.74	3.57	.13	3.67	.23	.33	2.41
10	M L L	2.08	.16	.88	.70	.35	.35	2.62	.14	1.30	.48	.38	.59
11	M L M	2.58	.15	1.93	.44	.26	1.13	2.94	.14	2.75	.36	.28	1.71
12	M L H	3.28	.14	3.21	.31	.17	2.77	3.43	.13	3.62	.27	.15	3.57
13	M M L	2.52	.16	.77	.50	.70	.24	2.99	.14	1.27	.41	.55	.49
14	M M M	2.62	.15	1.77	.40	.48	.75	3.21	.12	2.49	.31	.32	1.50
15	M M H	3.05	.14	3.23	.28	.29	2.19	3.41	.13	3.62	.25	.21	3.09
16	M H L	2.61	.16	.76	.44	.87	.21	3.09	.14	1.23	.41	.75	.38
17	M H M	2.81	.14	1.53	.34	.65	.55	3.09	.14	1.23	.41	.75	.38
18	M H H	3.43	.13	3.05	.24	.36	1.87	3.48	.13	3.69	.23	.29	2.62
19	H L L	2.00	.16	.97	.59	.33	.44	2.84	.15	1.30	.56	.42	.53
20	H L M	2.94	.15	1.68	.46	.28	.92	3.26	.13	2.65	.37	.25	1.75
21	H L H	3.11	.15	3.03	.31	.18	2.59	3.51	.13	3.96	.27	.16	3.76
22	H M L	2.32	.17	.97	.53	.64	.31	2.98	.14	1.23	.44	.55	.47
23	H M M	3.15	.13	1.54	.39	.46	.68	3.28	.13	2.54	.33	.33	1.48
24	H M H	2.91	.14	3.40	.29	.25	2.43	3.36	.14	3.86	.27	.21	3.19
25	H H L	2.17	.18	.94	.46	.84	.26	2.85	.15	1.32	.40	.67	.45
26	H H M	2.86	.14	1.71	.32	.55	.71	3.33	.13	2.64	.33	.43	1.30
27	H H H	3.37	.14	3.08	.26	.34	1.90	3.57	.13	3.64	.24	.27	2.74

a/ Average dry matter yield of three replicates for four harvests in g/pot.
b/ Grass tetany ratio of kikuyugrass.

Table 40. Mineral composition, dry matter yield and grass tetany ratio of kikuyugrass grown in Wahiawa (B) soil at pH 5.0 and pH 6.0.

Trt	CaMgK	DM[a/] (g)	P	K	Ca	Mg	R[b]	DM (g)	P	K	Ca	Mg	R
			--------%	-------					-----%	--------			
		------- pH 5.0 -------						-------- pH 6.0 -------					
1	L L L	1.88	.27	1.96	.64	.52	.66	2.94	.27	2.12	.70	.65	.62
2	L L M	2.20	.23	3.39	.50	.38	1.54	3.65	.22	3.75	.51	.46	1.51
3	L L H	3.42	.20	4.78	.38	.32	2.70	4.61	.19	5.81	.33	.30	3.60
4	L M L	2.32	.27	2.07	.52	.82	.57	3.74	.25	1.75	.65	.93	.41
5	L M M	3.09	.24	3.16	.46	.65	1.07	3.52	.22	4.15	.45	.57	1.55
6	L M H	3.97	.19	4.63	.35	.47	2.11	4.50	.19	6.16	.30	.36	3.52
7	L H L	2.30	.30	1.89	.42	1.02	.46	3.12	.31	2.46	.54	.99	.58
8	L H M	3.13	.25	3.47	.33	.75	1.15	4.10	.24	4.18	.39	.68	1.40
9	L H H	4.35	.21	4.55	.29	.62	1.77	4.34	.24	5.93	.28	.47	2.87
10	M L L	1.71	.31	2.71	.59	.44	1.06	3.75	.26	1.83	.82	.61	.51
11	M L M	2.23	.28	3.67	.50	.36	1.72	4.22	.23	3.96	.51	.44	1.63
12	M L H	2.75	.22	5.15	.34	.27	3.35	5.35	.20	5.65	.35	.30	3.43
13	M M L	2.46	.28	1.88	.57	.75	.53	4.19	.26	1.63	.71	.89	.38
14	M M M	3.26	.24	3.15	.45	.63	1.09	4.45	.23	3.88	.50	.57	1.38
15	M M H	4.35	.19	5.03	.36	.44	2.35	4.30	.20	6.33	.34	.35	3.55
16	M H L	2.73	.30	2.03	.46	.98	.50	3.64	.32	2.13	.69	1.03	.45
17	M H M	3.53	.25	3.11	.42	.80	.91	3.93	.26	4.17	.49	.68	1.32
18	M H H	3.83	.21	5.26	.29	.49	2.46	5.22	.24	5.97	.32	.46	2.83
19	H L L	2.53	.32	1.63	.74	.52	.52	2.97	.28	2.31	.83	.65	.62
20	H L M	3.69	.27	2.67	.64	.39	1.06	3.89	.22	4.15	.57	.41	1.71
21	H L H	3.98	.21	4.49	.48	.28	2.42	4.27	.21	6.10	.39	.27	3.77
22	H M L	2.45	.31	1.89	.67	.86	.46	4.25	.25	1.73	.86	.82	.40
23	H M M	3.57	.27	2.97	.53	.66	.93	4.47	.22	4.43	.56	.54	1.56
24	H M H	4.20	.22	4.85	.39	.45	2.16	4.39	.21	6.07	.40	.36	3.12
25	H H L	2.51	.38	2.32	.59	.93	.56	4.25	.28	1.89	.87	1.01	.38
26	H H M	3.49	.25	3.15	.50	.77	.91	4.67	.22	3.79	.58	.60	1.23
27	H H H	4.51	.25	4.64	.37	.56	1.84	6.19	.21	5.59	.39	.43	2.57

a/ Averge dry matter yield of three replicates for four harvests in g/pot.
b/ Grass tetany ratio of kikuyugrass.

Table 41. Soil chemical analysis for Maile soil at the end of the study.

Trt	Ca	Mg	K	pH	P	K	Ca	Mg	pH	P	K	Ca	Mg
					-------ppm-------					--------pm-------			
				----- pH 5.0 -----					------ pH 6.0 -----				
1	L	L	L	5.3	25.2	19	547	34	5.8	26.6	28	1225	64
2	L	L	M	5.4	24.7	57	584	54	5.8	27.8	98	1254	79
3	L	L	H	5.4	20.4	365	597	64	5.8	22.3	1122	1283	80
4	L	M	L	5.3	26.8	25	588	79	5.7	23.7	25	1211	187
5	L	M	M	5.3	25.7	33	593	90	5.8	17.3	86	1211	213
6	L	M	H	5.4	26.8	343	608	128	5.8	24.5	1016	1266	278
7	L	H	L	5.3	28.2	18	639	297	5.6	22.9	26	1256	685
8	L	H	M	5.2	23.9	42	588	369	5.7	28.1	122	1222	611
9	L	H	H	5.3	24.5	302	565	359	5.7	27.8	1002	1259	748
10	M	L	L	5.4	18.6	33	766	42	5.9	22.5	37	1675	56
11	M	L	M	5.4	25.3	35	688	48	5.9	24.5	166	1667	84
12	M	L	H	5.4	25.2	312	797	59	5.9	25.1	1006	1701	110
13	M	M	L	5.4	25.3	27	786	74	5.8	32.9	19	1691	178
14	M	M	M	5.4	27.6	40	825	92	5.8	28.2	129	1649	221
15	M	M	H	5.4	25.7	332	832	137	5.8	22.7	1044	1734	279
16	M	H	L	5.3	26.2	22	815	262	5.8	27.4	22	1720	637
17	M	H	M	5.3	24.6	33	823	318	5.8	24.7	81	1650	658
18	M	H	H	5.3	26.6	289	814	385	5.8	22.7	976	1660	714
19	H	L	L	5.3	27.4	24	1057	74	5.9	22.1	22	2313	55
20	H	L	M	5.3	25.0	30	1048	40	5.9	28.4	80	2294	79
21	H	L	H	5.4	24.5	312	1032	54	5.9	25.1	865	2475	115
22	H	M	L	5.3	23.6	29	1060	104	5.8	28.4	30	2297	205
23	H	M	M	5.3	28.8	30	1031	92	5.9	29.4	122	2264	235
24	H	M	H	5.3	24.1	327	1087	127	5.9	22.5	875	2269	262
25	H	H	L	5.3	24.5	30	1046	324	5.7	21.9	29	2324	689
26	H	H	M	5.2	25.5	36	1066	313	5.7	23.3	96	2167	658
27	H	H	H	5.3	26.6	362	1031	403	5.8	22.5	1051	2439	813

Table 42. Soil chemical analysis for Wahiawa (B) soil at the end of the study.

Trt	Ca	Mg	K	pH	P	K	Ca	Mg	pH	P	K	Ca	Mg
					------ppm------					-----ppm-----			
				----- pH 5.0 -----					----- pH 6.0 -----				
1	L	L	L	4.3	269	46	859	27	4.9	295	39	1701	58
2	L	L	M	4.4	295	72	888	29	5.0	316	88	1761	67
3	L	L	H	4.4	281	184	880	31	5.0	326	242	1846	76
4	L	M	L	4.4	300	47	836	106	5.0	297	44	1708	219
5	L	M	M	4.5	292	117	863	105	5.0	302	85	1755	243
6	L	M	H	4.6	297	151	867	116	5.1	300	266	1796	241
7	L	H	L	4.5	311	45	824	366	5.0	299	34	1735	773
8	L	H	M	4.5	298	100	863	327	5.1	274	62	1761	739
9	L	H	H	4.6	304	150	865	394	5.0	333	284	1935	784
10	M	L	L	4.4	280	54	1143	37	5.3	293	45	2377	60
11	M	L	M	4.4	321	128	1103	36	5.4	319	84	2385	58
12	M	L	H	4.5	291	180	1181	34	5.4	333	213	2405	66
13	M	M	L	4.5	302	40	1119	99	5.4	315	45	2457	198
14	M	M	M	4.6	344	61	1180	121	5.5	325	63	2337	227
15	M	M	H	4.6	274	131	1212	111	5.3	332	308	2500	261
16	M	H	L	4.5	294	42	1235	395	5.3	324	36	2295	744
17	M	H	M	4.5	358	63	1242	352	5.4	323	71	2273	758
18	M	H	H	4.6	314	163	1227	413	5.3	341	210	2545	798
19	H	L	L	4.6	326	41	1537	23	5.4	364	39	2991	61
20	H	L	M	4.8	327	67	1453	18	5.5	336	84	2791	60
21	H	L	H	4.8	281	169	1343	33	5.5	356	254	3179	82
22	H	M	L	4.6	322	46	1438	108	5.6	324	38	2951	221
23	H	M	M	4.7	335	58	1447	93	5.6	371	71	2972	244
24	H	M	H	4.8	341	113	1544	108	5.6	352	260	3123	258
25	H	H	L	4.7	331	54	1543	376	5.5	350	40	2869	707
26	H	H	M	4.8	289	65	1571	366	5.6	321	94	3176	800
27	H	H	H	4.8	305	114	1518	363	5.6	298	256	2976	729

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